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Non-cosmological Signal Contributions to the *COBE*[1]-DMR Four-Year Sky Maps

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ABSTRACT

We limit the possible contributions from non-cosmological sources to the *COBE*-DMR four-year sky maps. The DMR data are cross-correlated with maps of rich clusters, extragalactic *IRAS* sources, $HEAO-1$ A-2 X-ray emission and 5 GHz radio sources using a Fourier space technique. There is no evidence of significant contamination by such sources at an rms level of ~ 8 μK (95% confidence level at 7° resolution) in the most sensitive 53 GHz sky map. This level is consistent with previous limits set by analysis of earlier DMR data and by simple extrapolations from existing source models. We place a 95% confidence level rms limit on the Comptonization parameter averaged over the high-latitude sky of $\delta y < 1 \times 10^{-6}$. Extragalactic sources have an insignificant effect on CMB power spectrum parameterizations determined from the DMR data.

Subject headings: cosmic microwave background — diffuse radiation — intergalactic medium

1. INTRODUCTION

In this *Letter* we address the potential for contamination of the cosmic microwave background (CMB) anisotropy in the *COBE*-DMR four-year sky maps by astrophysical foregrounds outside of our Galaxy. Following Bennett et al. (1992), we investigate possible contributions from non-cosmological sources by direct comparison of the sky maps with similar maps generated from extragalactic surveys.

Models of the point source contribution at the DMR frequencies (Toffolati et al., 1995) suggest a contribution $\Delta T/T < 10^{-7}$, well below the level at which they may be of concern. Simple frequency extrapolations of the *IRAS* point source fluxes (Gawiser & Smoot, 1996) reach the same conclusion. However, such calculations are not sensitive to the more extended diffuse emission which some of the maps considered here are.

2. METHOD

Inverse-noise-variance weighted combinations of the A and B channels in Galactic pixelization are formed at each of the DMR frequencies, the weights being (0.618, 0.382), (0.579, 0.421) and (0.382, 0.618) at 31.5, 53 and 90 GHz respectively. We cross-correlate the DMR maps with a given extragalactic sky map X over the high latitude sky, defined as a region with Galactic latitude $\mid b \mid > 20^\circ$ with additional cut sky regions at Ophiuchus and Orion (Bennett et al. 1996), and at specific positions in the extragalactic maps with missing or unusable data. Each map is then decomposed into Fourier coefficients using a basis of orthonormal functions explicitly computed on the available sky coverage (Górski 1994). This technique has the advantage of allowing exact exclusion of the physically unconstrained monopole and dipole components from the analysis, and makes full use of all of the avilable spatial (phase) information. The measured DMR map Fourier coefficients, $\mathbf{c}_{\rm DMR}$, can then be written in vector form as $\mathbf{c}_{\rm DMR} = \mathbf{c}_{\rm CMB} + \mathbf{c}_{\rm N} + \alpha_X \mathbf{c}_X$ where $\mathbf{c}_{\rm CMB}$, $\mathbf{c}_{\rm N}$ and $\mathbf{c}_X$ are the coefficients describing the true CMB distribution, the noise and the extragalactic map. α_X is now a coupling constant (with units μK X^{-1}) to be determined by minimizing

$$\chi^2 = (\mathbf{c}_{\rm DMR} - \alpha_X \mathbf{c}_X)^T \, \tilde{\rm M}^{-1} \, (\mathbf{c}_{\rm DMR} - \alpha_X \mathbf{c}_X)$$

where $\tilde{\mathbf{M}}$ is the covariance matrix describing the correlation between different Fourier modes on the cut-sky and is dependent on assumed CMB model parameters and the DMR instrument noise. The CMB may be described by a Harrison-Zel'dovich power law spectrum with rms quadrupole normalisation $Q_{rms-PS} = 18.5$ μK. The Fourier coefficient vectors contain spectral information over a range $[\ell_{min}, \ell_{max}]$, where ℓ_{min} is either 2 (quadrupole included) or 3 (quadrupole excluded). We set $\ell_{max} = 30$, which is sufficient to describe the cosmic content of the DMR data.

The coupling constant α has an exact solution

$$\alpha_X \;=\; \mathbf{c}_X\,\tilde{\mathrm{M}}^{-1}\,\mathbf{c}_{\mathrm{DMR}}/\mathbf{c}_X\,\tilde{\mathrm{M}}^{-1}\,\mathbf{c}_X$$

and a Gaussian error given by $\sigma^2(\alpha_X) = (\mathbf{c}_X\,\tilde{\mathrm{M}}^{-1}\,\mathbf{c}_X)^{-1}$.

The contribution of X to the DMR sky is the map $\alpha_X T_X$, which can be characterized by the rms amplitude $(\alpha_X T_X)_{rms}$ and peak-to-peak quantity $(\alpha_X T_X)_{pp}$. Both values are computed over the cut-sky after subtraction of a best fit monopole, dipole and, if appropriate, quadrupole.

3. ABELL-CORWIN-OLOWIN RICH CLUSTERS

Inverse Compton scattering of CMB photons from hot intracluster gas causes a decrement in the Rayleigh-Jeans part of the CMB spectrum, $\Delta T \;=\; -2yT_0$, where T_0 is the unperturbed CMB temperature and y, the Comptonization parameter, is a function of the integrated electron pressure along the line-of-sight. This Sunyaev-Zel'dovich effect (Sunyaev & Zel'dovich, 1980) may generate some of the temperature anisotropy observed by *COBE*-DMR. As in Bennett et al. (1993), we use a rich cluster map constructed from the data of Abell, Corwin & Olowin (1989, hereafter ACO) to place limits on this contribution. We therefore assume that the ACO rich cluster map is a good tracer of the spatial morphology of the large scale cluster gas distribution giving rise to the SZ effect, and that the richness class is a good indicator of the optical depth of the gas. Each pixel of the rich cluster map is a sum over the richness classes of all clusters in that pixel. The map is convolved with the DMR beam pattern (E.L. Wright et al., 1994). Additional versions of the map have been computed with different Abell richness thresholds, and by summing over different exponents of the richness class in a given pixel. No significant differences are seen for the different binning strategies. We report results for a minimum richness class threshold of 1, and simple binning by the richness class (ie. an exponent of 1).

Table 1 summarizes the results of the analysis. The SZ effect will generate approximately equal and negative α_X values over the three DMR frequencies. There are no significant correlations between the DMR sky maps and the ACO rich cluster map. The 31 GHz coupling coefficient is negative, though not at a statistically significat level. However, it is more likely due to anti-correlation between the ACO zone of avoidance and the DMR galactic signal. This is supported by the decrease in significance for the quadrupole excluded fit, which would remove a significant fraction of the Galactic emission.

4. *HEAO-1* A-2 X-RAY DATA

The $HEAO-1$ A-2 X-ray emission map, as discussed in Bennett et al. (1993) and provided by K. Jahoda with flux scale as in Jahoda & Mushotzky (1989), was reconvolved to the DMR beam profile and cross-correlated with the DMR sky maps. With the DMR custom Galactic cut, 3875 pixels remain at high latitude. Strong Galactic emission from the Ophiuchus and Orion regions common to both the X-ray and DMR maps is excised by this process. Nevertheless, there remain correlations in excess of $2\,\sigma$ which may be associated with either the LMC (a prominent high latitude feature in the $HEAO-1$ map) or perhaps from Galactic emission traced by the X-ray map. At 95% confidence we limit the contribution of anisotropy traced by the X-ray map to the DMR analysis to be $< 8\ \mu$K irrespective of its origin.

Since rich clusters of galaxies are bright X-ray sources the X-ray emission in the $HEAO-1$ map could also, in principle, trace the hot gases in these structures which give rise to the SZ effect (although the angular distribution of the X-ray emission and temperature anisotropy would be somewhat different). We might then expect some negative correlation with the DMR maps (since at DMR frequencies the SZ effect manifests itself as a temperature decrement), but in all cases the correlation constants are positive. We conclude, like Bennett et al. (1993), Boughn & Jahoda (1993), and Rephaeli (1993), that the fluctuations observed by $COBE$ are not generated by such a mechanism. A chance alignment of features of primordial CMB anisotropy with features in the X-ray map would give similar flat-spectrum correlations with $\sim 3\%$ probability.

5. 1.2 JANSKY *IRAS* GALAXIES

We consider a sample of $IRAS$ galaxies selected from the $IRAS$ point source catalog for which redshifts have been measured. Fisher et al. (1995) extend the 2 Jy survey of Strauss et al. (1992) to a flux limit of 1.2 Jy, resulting in a catalog of some 5321 galaxies with measured redshifts covering 87.6% of the sky. A map of the 1.2 Jy sky was generated as described previously using the $IRAS$ 100 μm flux, but excluding regions as prescribed in Strauss et al. (1990) and using a mask and software provided by Strauss (1995). The $IRAS$ 100 μm sky is dominated by emission from the Large Magellanic Cloud (LMC) but we are more interested in potentially significant correlations with the rest of the map. Fortunately, the mask does exclude a region around the LMC. After applying the mask and the custom DMR galactic cut 3620 pixels remain. The $IRAS$ galaxies show notable structure around Virgo, Coma and in the supergalactic plane; however, no correlations exceed $\sim 2\,\sigma$ significance.

6. 5 GHZ RADIO SOURCES

We have combined data from the 87 GB 5 GHz survey of Gregory & Condon (1991) with new southern hemisphere data from the Parkes-MIT-NRAO (PMN) surveys. The PMN data

are divided into declination ranges as follows: the southern survey covers -87°.5 < δ <-37°(A.E. Wright et al., 1994), the zenith -37°< δ <-29°(Tasker et al., 1996), the tropical -29°< δ <-9°.5 (Griffith et al., 1994) and the equatorial -9°.5 < δ <+10° (Griffith et al., 1995). Together with the 87 GB coverage of 0°< δ <+75°, we should in principle be able to construct a nearly all-sky radio source map. Unfortunately, the various data sets are complete at different flux limits, ranging from $\sim$ 25 mJy for the 87 GB data and parts of the southern survey to $\sim$ 72 mJy for the zenith survey (A.E. Wright, 1995 – private communication). Two maps were therefore assembled: the first with a lower flux threshold of 40 mJy and *excluding* the zenith survey data, the second with a threshold of 72 mJy and *including* the zenith survey. In both cases, data in the declination range 0°< δ <10°were taken from the 87 GB survey: although some inconsistencies exist between the 87 GB and PMN catalogs over this common declination band (Gregory et al., 1994), small positional uncertainties are unlikely to be of importance after smoothing to DMR resolution. Large systematic differences in the flux densities would generate a strong gradient between the northern and southern celestial hemispheres which is not observed in the maps[8].

Cross-correlation of both maps with the DMR data shows no statistically significant difference in the results, and we have elected to continue the analysis with the 72 mJy flux limited map which has the greater sky coverage ($\sim$ 12 steradians). Off the Galactic plane much of the signal appears towards Virgo. After applying the extended galaxy cut to the map 3690 usable pixels (covering $\sim$ 7.5 steradians) remain. No correlations exceed the $\sim 1\,\sigma$ level.

7. JOINT ANALYSIS

We have extended the Fourier space template fitting technique as described in Górski et al. (1996) to enable us to fit the four non-cosmological template maps to the three DMR frequencies simultaneously. This forces the CMB distribution (in thermodynamic units) to be invariant between the three frequencies, thus allowing an improved determination of the extent of chance cosmic or noise alignments with the template maps. We include the quadrupole components in the analysis, and determine the galactic contribution by fitting to two Galactic templates – the *DIRBE* 140 μm map and a radio survey at 408 MHz (Haslam et al., 1981). Kogut et al. (1996a) have discussed the effectiveness of these two maps in accounting for Galactic dust, free-free and synchrotron emission, and the Galactic microwave emission at high latitudes has been reconsidered in the light of the DMR four-year results in Kogut et al. (1996c). Orthonormal functions were computed for the sky coverage common to all template maps, leaving 3423 pixels after the

[8]Furthermore, replacing the PMN southern survey with an alternative version from Gregory et al. (1994) generated in a similar fashion to the 87 GB catalog also yields statistically consistent results.

custom DMR Galactic cut excision (the region around the LMC was therefore masked since it is removed in the *IRAS* 1.2 Jy analysis). No constraints were imposed on the spectral dependences of the template maps over the DMR frequencies. Since the method considers the three DMR maps simultaneously, it results in the strongest constraints on non-cosmological correlations. 18 coefficients were determined, the non-Galactic 12 of which are summarized in column (8) of Table 1. The results are in excellent agreement with the single DMR channel-to-template fits.

The correlation between the 31 GHz map and the ACO Rich Clusters template becomes positive, following the trend evident from the fits with and without quadrupole. This supports the previous conclusion that the initially negative values for the α_X coefficient are due to a chance alignment of features rather than any genuine SZ contribution. Although there is some cross-talk between the 31 GHz cluster and *DIRBE* correlations, this is not unexpected since the ACO zone of avoidance anti-correlates with the predominantly quadrupolar Galactic signal. Typical uncertainties in α give a 95% confidence level upper limit on the 7° rms contribution traced by the ACO map of better than ~ 6 μK for the sensitive 53 and 90 GHz channels. This yields a corresponding 95% CL rms limit on the Comptonization parameter averaged over the high latitude sky of $\delta y = -(\delta T/2T) \simeq 1 \times 10^{-6}$. If we interpret the limits from the $HEAO-1$ A-2 correlations similarly (i.e. as limits on SZ related fluctuations), this limit improves to better than 8.4×10^{-7}. Rephaeli (1993) has independently searched the $HEAO-1$ A-2 data base to place direct bounds on the properties of hot gas in superclusters of galaxies, placing a limit on the mean Comptonization parameter of a few $\times 10^{-7}$, in excellent agreement with the results here.

In fact, the correlations between the DMR maps and both the ACO clusters and $HEAO-1$ A2 X-ray map are predominantly positive, in contrast to the expected signature from the SZ effect. Such a signal could be indicative of radio sources embedded in the clusters. Since the cross-correlation between these maps and the 5 GHz radio sources is negligible, this would require that the dominant sources at DMR frequencies had flat spectra and were below the detection threshold at the lower frequency. We place a conservative 95% CL upper limit on the rms *emission* from clusters over the high latitude sky of 10 μK.

Note that, with the exclusion of the LMC region from the joint analysis sky coverage, the $2.5\,\sigma$ correlation between the 53 GHz sky map and the $HEAO-1$ A2 X-ray map is significantly decreased. This is also the case when a single map correlation is computed between the 53 GHz and X-ray maps after removing a circular region of 10° radius on the LMC (for which α falls to $\sim 20 \pm 15$). A significant fraction of the correlation appears to be associated with this region. Bennett et al. (1993) predicted that the LMC, and specifically the giant HII region 30 Doradus, might contribute a signal of order 50 μK at 53 GHz. Kogut et al. (1994) determined an upper limit of 87 μK (95% confidence level) from the two year sky maps with a point source fitting technique, in good agreement with this prediction. Using the peak-peak limits from the earlier fits including this region, we place 95% upper limits to the antenna temperature microwave emission of the LMC of 109, 49 and 57 μK at 31.5, 53 and 90 GHz respectively.

In addition, the correlation coefficients between the Galactic templates and the 4-year maps are in good agreement with those determined in Kogut et al. (1996c). For comparison, at 53 GHz, we find $\alpha_{140\mu\mathrm{m}} = 2.45 \pm 1.04$, $\alpha_{408\mathrm{MHz}} = 0.36 \pm 0.76$ to convert the Galactic templates to antenna temperature in μK. There is no significant cross-talk between the Galactic and extragalactic templates.

Finally, we have tested the sensitivity of the fits to the assumption that the cosmic signal present in the DMR sky maps is well described by a power law spectrum with $Q_{rms-PS} = 18.5$ μK and $n = 1$ by running a full grid of power law models as in Górski et al. (1996). After weighting the α coefficients by the likelihood function determined for the grid of cosmological models, we find that the Harrison-Zel'dovich model computations are perfectly adequate. Moreover, we find that the effect of the non-cosmological template subtraction on the most likely (Q_{rms-PS}, n) is to shift these values by $\sim$0.1 μK and -0.06 respectively. We conclude that there is no evidence for significant non-cosmological signal contamination of the DMR sky maps.

8. CORRELATION WITH INDIVIDUAL BRIGHT CLUSTERS

In the previous sections, we have demonstrated that there is no evidence of non-cosmological signal detection based on correlation of the DMR maps with fixed source signal templates. This limit applies to the spatial average of sources at high Galactic latitudes, and so we consider here whether individual bright clusters of galaxies are detected in the DMR data. Nearby clusters are more likely to contribute a measurable signal in the DMR sky maps given their large angular extent. We consider the mean temperatures in the DMR maps towards 5 nearby clusters to search for indications of SZ decrements or radio and dust emission from galaxies within the cluster (which are competing effects at the DMR frequencies, and any limits should be considered in light of this). A "ring" technique, as utilized previously in Bennett et al. (1993) and Kogut et al. (1994), computes the difference between the mean temperature of pixels within a disk of radius θ and those in the surrounding annulus of equal area. This technique should be sensitive to low surface Comptonization. The results summarized in Table 2 are for $\theta = 10^\circ$. There are no significant detections when a weighted mean is taken over the three DMR frequencies. An upper limit of 38 μK can be placed on emission from nearby clusters.

Herbig et al. (1995) have detected the SZ effect in Coma with a central decrement of -505 ± 92 μK (after large corrections for discrete radio sources and applying a model for the X-ray atmosphere of the cluster). It is not surprising that DMR is unable to detect this anisotropy given the large beam dilution. The Coma cluster has an approximate $0^\circ.5$ FWHM, which by virtue of its ratio to the DMR beam solid angle implies an expected signal of less than 3 μK. A limit of $\delta y < 7 \times 10^{-6}$ can be established for Comptonization by nearby clusters (from the maximum weighted error in Table 2).

9. DISCUSSION AND CONCLUSIONS

We have examined the *COBE* DMR 4-year sky maps for evidence of non-cosmological signal contamination and find none. A simultaneous fit of the three DMR frequencies to two Galactic templates and four extragalactic sky maps yields rms limits due to the extragalactic correlations alone of $\sim$ 18, 8 and 11 μK at 31.5, 53 and 90 GHz respectively (95% confidence levels). These limits are higher than those predicted by simple point source models, but are limited by the DMR noise levels and might be regarded as somewhat conservative. The contribution from non-cosmological sources is insubstantial compared to the $\sim$ 35 μK rms anisotropy signal detected in the DMR sky maps at 7° resolution (Banday et al. 1996). Moreover, extragalactic template corrections perturb the maximum likelihood power spectrum analysis of the *COBE*-DMR data for power law cosmological models insignificantly: the best fit parameters (Q_{rms-PS}, n) are only shifted by $\sim$0.1 μK and -0.06 respectively from their uncorrected values.

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Table 1: Cross-correlation results and non-cosmological signal contributions.

	quadrupole included			quadrupole excluded			joint analysis		
Freq (GHz)	α_X (μK X^{-1})	$(\alpha T_X)_{rms}$ (μK)	$(\alpha T_X)_{pp}$ (μK)	α_X (μK X^{-1})	$(\alpha T_X)_{rms}$ (μK)	$(\alpha T_X)_{pp}$ (μK)	α_X (μK X^{-1})	$(\alpha T_X)_{rms}$ (μK)	$(\alpha T_X)_{pp}$ (μK)
ACO Rich Clusters									
31	-10.34 ± 8.74	6.2 ± 5.3	47.9 ± 39.9	-4.60 ± 9.64	2.1 ± 4.4	17.9 ± 37.4	0.37 ± 8.51	0.2 ± 5.0	1.3 ± 30.7
53	1.72 ± 4.78	1.0 ± 2.9	7.8 ± 21.8	2.79 ± 4.97	1.3 ± 2.3	10.8 ± 19.3	5.85 ± 4.52	3.4 ± 2.6	21.1 ± 16.3
90	3.30 ± 6.04	2.0 ± 3.6	15.1 ± 27.5	3.77 ± 6.38	1.7 ± 2.9	14.6 ± 24.8	1.10 ± 5.52	0.6 ± 3.2	4.0 ± 19.9
$HEAO-1$ **A2 X-ray sources**									
31	46.60 ± 23.52	7.5 ± 3.8	112.5 ± 56.8	43.71 ± 23.69	6.8 ± 3.7	102.8 ± 55.7	52.87 ± 26.79	7.6 ± 3.8	113.2 ± 57.35
53	28.12 ± 11.09	4.6 ± 1.8	67.9 ± 26.8	27.97 ± 11.10	4.4 ± 1.7	65.8 ± 26.1	4.65 ± 12.14	0.7 ± 1.7	10.0 ± 26.0
90	22.84 ± 14.93	3.7 ± 2.4	55.1 ± 36.0	22.89 ± 14.97	3.6 ± 2.3	53.8 ± 35.2	15.54 ± 16.21	2.5 ± 2.3	37.5 ± 34.7
1.2 Jy $IRAS$ **Galaxies**									
31	0.75 ± 0.42	8.0 ± 4.5	124.1 ± 69.3	0.85 ± 0.42	8.7 ± 4.3	138.8 ± 68.6	0.48 ± 0.37	5.3 ± 4.1	80.3 ± 61.9
53	0.21 ± 0.19	2.3 ± 2.1	35.2 ± 32.4	0.22 ± 0.20	2.3 ± 2.0	36.3 ± 31.7	0.04 ± 0.17	0.5 ± 1.9	7.4 ± 28.3
90	0.01 ± 0.26	0.2 ± 2.8	2.5 ± 43.3	0.02 ± 0.26	0.2 ± 2.7	2.8 ± 42.6	0.27 ± 0.22	3.0 ± 2.4	45.0 ± 37.1
5 GHz (87 GB/PMN) Radio Sources									
31	0.09 ± 0.14	2.9 ± 4.4	69.9 ± 106.8	0.08 ± 0.15	2.5 ± 4.4	60.7 ± 105.7	-0.09 ± 0.15	2.7 ± 4.6	65.4 ± 111.0
53	0.09 ± 0.06	2.6 ± 1.9	62.7 ± 45.9	0.09 ± 0.06	2.6 ± 1.9	62.5 ± 45.3	-0.01 ± 0.06	0.4 ± 1.9	9.4 ± 47.0
90	0.11 ± 0.09	3.4 ± 2.6	81.7 ± 62.9	0.11 ± 0.09	3.4 ± 2.6	81.8 ± 62.1	0.06 ± 0.09	1.7 ± 2.6	40.9 ± 63.0

Note – rms and peak-peak values are computed after subtraction of the monopole, dipole and, where appropriate, quadrupole distributions over the uncut regions of the sky. All temperatures are in thermodynamic units.

Table 2: Fitted amplitudes toward Sunyaev-Zel'dovich candidate clusters (μK).

Source	T_{31}	T_{53}	T_{90}	Weighted Mean
Coma	-3 ± 52	4 ± 16	-59 ± 25	-14 ± 13
	-63 ± 53	5 ± 16	20 ± 26	5 ± 13
Virgo	54 ± 59	-21 ± 17	33 ± 26	-2 ± 14
	-35 ± 60	10 ± 17	-33 ± 27	-4 ± 14
Perseus-Pisces	16 ± 67	1 ± 24	3 ± 37	3 ± 19
	-32 ± 69	25 ± 24	4 ± 38	15 ± 19
Hercules	105 ± 51	9 ± 19	-3 ± 30	15 ± 15
	-54 ± 52	13 ± 19	15 ± 31	8 ± 15
Hydra	-112 ± 62	-29 ± 21	9 ± 32	-25 ± 17
	77 ± 64	-18 ± 21	12 ± 33	-3 ± 17

Note – First line for each source refers to fitted amplitude of weighted sum map, the second refers to the (A-B)/2 difference map. All amplitudes are thermodynamic temperature units.

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