MEASUREMENTS OF THE SCATTERING OF THE MICROWAVE BACKGROUND RADIATION IN CLUSTERS OF GALAXIES

M. Birkinshaw
Department of Radio Astronomy, University of California
Berkeley, California 94720

Results for the decrements in the microwave background radiation towards the centres of 13 clusters of galaxies are presented. It is shown that these data imply central gas densities of about 2×10^{-24} kg m^{-3} and cluster masses of about 5×10^{45} kg.

INTRODUCTION

The prediction that a detectable diminution in the brightness of the microwave background radiation towards an X-ray cluster of galaxies should exist if the X-radiation is of thermal bremsstrahlung origin (Sunyaev and Zeldovich 1972) lead a number of workers to attempt to measure such an effect (Parijskij 1973a,b,c; Gull and Northover 1976; Lake and Partridge 1977; Birkinshaw, Gull and Northover 1978a,b; Rudnick 1978; Perrenod and Lada 1979). The overall lack of agreement between these workers may be ascribed to (1) the extreme difficulty of measuring brightness temperature differences of order 1 mK in the presence of much larger atmospheric effects that vary on timescales from hours to weeks, and (2) the possiblity of very small systematic errors entering the data from non-idealities in the beamshape or side-lobe structure of the telescope used.

In order to check against these effects, many hours of data using a carefully-tested instrument must be collected. This paper presents the latest results from about 4500 hours of observation towards, or almost towards, the centres of 13 clusters of galaxies. Full details of the experimental technique and other results will appear elsewhere (Birkinshaw, Gull and Northover 1980).

METHODS

The telescope used for these observations was the 25-m paraboloid of the SRC Appleton Laboratory at Chilbolton, Hampshire. At the observing frequency chosen (10.6 GHz), the telescope has a beamwidth

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of about 4.5 arcmin and an efficiency of 0.55. The receiver system had a noise temperature of 180 K and a bandwidth of 250 MHz.

A twin-beam system in the configuration described by Birkinshaw *et al.* (1978b) was used to eliminate the strongest atmospheric effects. The 1-minute temperature difference measurements recorded by this technique were then tested in a complex, but statistically-unbiased, manner to remove interference spikes (caused by pigeons, helicopters or Hampshire thunderstorms), to detect biased data-segments and to find interfering sources in the reference arcs around each point observed. It was found that subtle, long-term, atmospheric noise fluctuations severely degraded the sensitivity of the system, so that very long integration times were necessary to achieve measurement accuracies of 0.3 mK or better. The final results from this analysis were slightly adjusted for temperature contributions from the (small angular size) sources detected in interferometric surveys at other frequencies than that used to search for a decrement in the microwave background.

RESULTS

The results at (or near, if the observing position was changed to avoid strong radio sources) the centres of the well-observed clusters are shown in Table 1. It can be seen that for A 576, 2218, and 2319

Table 1. Results

Cluster	Observing Time (hr)	Measured Microwave Background Decrement, ΔT, corrected for radio sources (mK)
A 71	20	+0.29 ± 0.54
A 347	35	+0.34 ± 0.29
A 376	79	+1.22 ± 0.35
A 478	106	-0.71 ± 0.47
A 576	190	-1.12 ± 0.17
A 665	107	-0.53 ± 0.22
A 1656*	63	-0.41 ± 0.35
A 1904	24	+0.55 ± 0.40
A 2125	124	-0.39 ± 0.22
A 2142	40	-1.4 ± 1.0
A 2218	137	-1.05 ± 0.21
A 2319*	50	-0.77 ± 0.28
A 2666	175	+0.34 ± 0.29
Blank sky	114	+0.03 ± 0.21

* Near, not at, cluster centre

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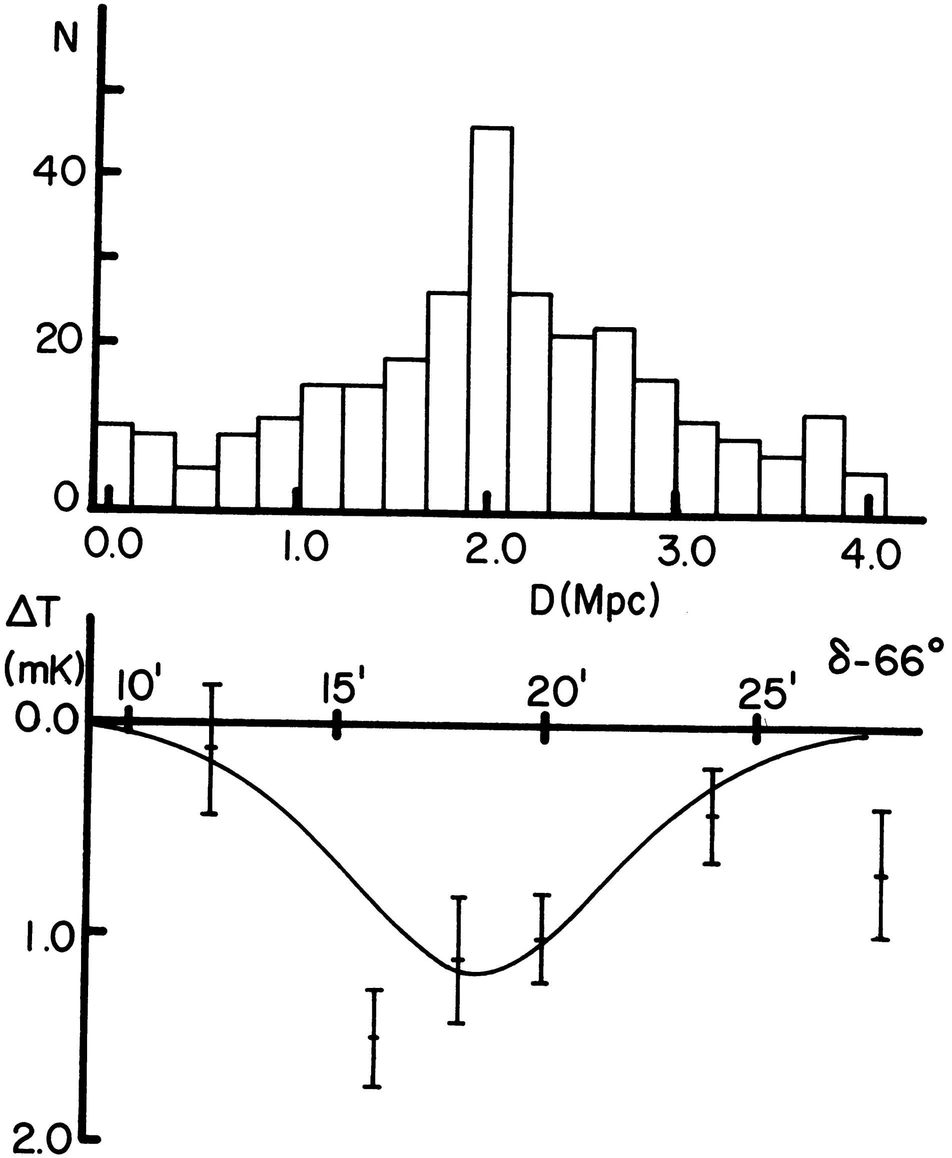

Figure 1. The galaxy strip-count, N, in arcminute bins and the observed temperature decrement at each point, ΔT, plotted as functions of declination (1950.0 coordinates). The solid line is the ΔT profile deduced from a reasonable model atmosphere lying in the potential well defined by the galaxy counts and convolved with the telescope beamshape. The linear scale, D, at the distance of the cluster is also indicated ($z = 0.168$, $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$).

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a cooling effect at a significance greater than 2.5σ has been found. The other results may be consistent with zero decrement plus a confusion distribution from flat-spectrum background sources. A strong check on systematic error is provided by the blank-sky observation, made at the same declination as the A 576 observation, but 4 hours later in RA, so that an observation of A 576 could be followed immediately by one on the blank sky.

In addition, several scans have been made. Figure 1 shows one of these, the NS scan for A 2218, where the measurements are shown plotted with the galaxy count across the cluster and the predictions of a reasonable model for the gas distribution [described in Birkinshaw *et al.* (1980)]. The close positional agreement between the large background decrements and the peak galaxy count comprises the best evidence for a detection of a real background decrement yet available.

GAS PARAMETERS

From the cluster-centre results, and a reasonable model for the cluster gas and galaxy distributions, model-dependent estimates of the central density of the gas responsible for the X-ray emission and the cluster mass may be found. These results are shown in Table 2 -- for some clusters only limits to the parameters are derivable due to the lack of significant X-ray or microwave-decrement detections. The errors in these parameters are large and not marked in the Table -- but the scatter of results is fairly small about values

central gas density $\sim 2 \times 10^{-24}$ kg m^{-3}

total cluster mass $\sim 5 \times 10^{45}$ kg

Table 2. Model-dependent derived parameters of the clusters

Cluster	Central gas density 10^{-24} kg m^{-3}	Cluster mass 10^{46} kg
A 71	<2.7	-
A 347	<0.8	-
A 478	4.3	0.3
A 576	1.0	2.5
A 665	<11.0	>0.1
A 1656	2.2	0.8
A 1904	<2.1	<0.2
A 2125	<14.3	>0.1
A 2142	3.2	0.9
A 2218	2.1	1.7
A 2319	3.3	0.5
A 2666	<1.1	<0.6

If the gas is highly clumped these results scale with the clumping parameter to the powers 0.4 and -0.4 respectively.

CONCLUSIONS

The main conclusions of this work are:

1. the observed temperature decrements agree qualitatively with those expected on the basis of the *new* X-ray data on clusters of galaxies; and

2. the central gas densities in the clusters detected here are deduced to be about 2×10^{-24} kg m^{-3}, and the cluster masses are about 5×10^{45} kg, agreeing with their virial masses.

In any future continuation of this work, the following points should be noted:

1. These observations were atmosphere-limited, and long integration times were needed to eliminate all timescales and amplitudes of atmospheric signal. Even working at the comparatively low frequency of 10.6 GHz, the use of a better site than Chilbolton would be a good idea;

2. On the other hand, observations with other telescopes are often affected by telescope-generated effects -- which must be checked against carefully before attempting to use any telescope for this work;

3. For observing distant clusters, a narrower telescope beam than that used here would be desirable -- a factor of at least 2 increase in the peak decrement for A 2218 should be seen if a beamwidth less than about 2 arcmin were to be used; and

4. Spectral studies of the decrement would be interesting, and would limit theoretical models for the cluster environment.

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DISCUSSION

Ford: What is the dependence of ΔT on z if the cluster X-ray source does not evolve, and what is the optimum z for measuring microwave diminution?

Birkinshaw: For any given telescope beamwidth and beamthrow, the optimum z is determined principally by the criterion that the beamwidth should be less than ~ 2 cluster core radii. Of less importance is that the beamthrow should exceed ~ 5 core radii. Thus, the configuration described above works most efficiently at z ~ 0.07.

Peebles: Would you indicate which of the clusters you observe are observed to be X-ray sources? Is there a correlation between X-ray detection and negative δT?

Birkinshaw: All the clusters with the exceptions of A 665 and 2125 have at some stage been said to be detectable in the X-ray waveband. An investigation of any correlation between ΔT and the X-ray flux density (or, more correctly, the X-ray luminosity) must await complete, and accurate, X-ray flux measurements. However, the constancy of values of $\rho(0)$ and M in Table 2 indicates the existence of such a correlation.

Boynton: With regard to the status of A2218 as an X-ray source, Steve Murray, Bob Schommer, and I have made a 4 x 10^4-sec exposure with the high resolution imager of the Einstein Observatory. We find the flux level is within a factor of 2 of the Ariel V upper limit. This cluster appears symmetric and centrally condensed. Model fits suggest that the temperature is rather high, not inconsistent with the values required by your microwave decrement measurement. We were somewhat surprised by this outcome.

N. Bahcall: A576, one of the two clusters with significant ΔT diminution detection, is a rather low-luminosity X-ray cluster and presumably of low density of hot gas.

Silk: I have observed Abell 576 with the IPC of the Einstein Observatory. The X-ray flux is about 1/6 of the Uhuru flux, but in agreement with other satellite measurements, making A576 a relatively low-luminosity X-ray cluster (9×10^{43} erg s^{-1} over 0.2 to 3 keV). However, the X-ray distribution is relatively uniform, spherically symmetric, and centrally condensed.