SCATTERING OF THE MICROWAVE BACKGROUND IN CLUSTERS OF GALAXIES

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## I. INTRODUCTION

Evidence from X-ray observations of clusters of galaxies suggests that they contain intergalactic plasma at a temperature of approximately $10^8$ K which emits thermal bremsstrahlung (cf. Lea et al. 1973). Although numerous models for the origin and distribution of the plasma have been presented (cf. Gould and Raphaeli 1978), the amount and distribution of the plasma is still not certain. Several years ago, Sunyaev and Zel-dovich (1972) pointed out another observable consequence of hot gas in clusters of galaxies: inverse Compton scattering by electrons in the plasma would increase the energy of photons of the microwave background as these photons pass through the cluster. The fractional change in intensity of the microwave background is:

$$\frac{\Delta I}{I} = \frac{xe^x}{e^x-1}\left[\frac{x}{\tanh\frac{x}{2}} - 4\right]\int_o^\tau \frac{kT_e}{m_e c^2}\, d\tau \tag{1}$$

where $\tau$ is the optical depth for Thomson scattering through the cluster, $T_e$ is the electron temperature of the plasma, $m_e$ is the electron mass, $x = h\nu/kT_r$, and $T_r$ is the temperature of the microwave background radiation, which we take to be 2.8°K. It is worth noting explicitly that this effect lowers the intensity (and therefore the antenna temperature) of the microwave background in the Rayleigh-Jeans region. This follows from the fact that the inverse Compton process conserves photon number while increasing the photon energy. Since estimates of the optical depth for Thomson scattering are uncertain, $\Delta I/I$ cannot be precisely predicted. Estimates varying from $10^{-5}$ to $3 \times 10^{-4}$ have been published, based on different models for the distribution of the plasma (see Gull and Northover, 1975; Sarazin and Bahcall, 1977; or Gould and Rephaeli, 1978).

The detection of this effect in clusters of galaxies would offer several benefits:

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(1) It would confirm the existence of plasma in the clusters thereby strengthening the hypothesis that it is thermal bremsstrahlung which produces the observed X-ray flux from clusters;

(2) since $\Delta I/I$ is proportional to the electron number density, $n_e$, whereas X-ray flux is proportional to $n_e^2$, observations of both would permit $n_e$ and the so-called "clumping factor", $\langle n_e^2\rangle/\langle n_e\rangle^2$, to be found, and this in turn would help discriminate among the models for the distribution of the plasma;

(3) combined X-ray and microwave observations can provide independent measures of $H_o$ and $q_o$ (Birkinshaw, 1979; Boynton and Murray, 1978; Cavaliere, Danese and De Zotti, 1978; Gunn, 1978; Silk and White, 1978); and finally

(4) detection of the effect would confirm the non-local origin of the microwave background.

## II. OBSERVATIONAL CONSIDERATIONS

### i) Observations by other groups

Several other groups have sought or are seeking to detect the inverse Compton cooling of the microwave background produced by cluster plasma. Pariiskii, working at a wavelength of 4 cm reported a positive detection of approximately $-10^{-3}$ K or -1 mK for the Coma cluster, a result in agreement with the early observations of Gull and Northover (1976) at a wavelength of 3 cm, but not with the subsequent analysis of Birkinshaw et al. (1978, hereafter BGN). Birkinshaw will be describing their observations of several other Abell clusters, most of them X-ray sources and their detection of the effect in two or possibly three of them. However, Rudnick (1978) observing at 2 cm, reported no statistically significant evidence for cooling of the microwave background by the clusters he has observed (at roughly comparable sensitivity), though he now believes he sees cooling in Abell Cluster 2218 (private communication, 1979). Perrenod and Lada (1979, hereafter PL) claim roughly $2\sigma$ results in three clusters. The apparent disagreement reflects the difficulty of these observations (see Rudnick, 1978). The expected signals are small. Most clusters contain radio sources which may produce spurious signals (these could be of either sign in an observation which employs beam switching). Finally, the plasma itself will emit bremsstrahlung radiation even at centimeter wavelengths, emission which may mask the signal sought.

### ii) Our work at 9 mm

In view of these problems, we decided to make our observations at a shorter wavelength than used by others; $\lambda$ = 9 mm, using the 11 meter NRAO telescope in Tucson. Using a short wavelength offered the three advantages summarized in Table 1 from Rudnick (1978). First, most radio

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TABLE 1[1]

Possible Contributions to Sky Brightness (mK)

| Source | Antenna Temperature | Brightness Temperature | | |
|---|---|---|---|---|
| | Cluster Radio Galaxies | Diffuse Cluster Sources | Galactic Structure | Confusion |
| BGN ($\lambda$ = 2.8 cm, D = 26 m) | $\lesssim$ 4. | 0.6 | 0.06 | 0.3 |
| Rudnick ($\lambda$ = 2 cm, D = 42 m) | $\lesssim$ 5(2') - $\leqslant$ 0.4(24') | 0.2 | 0.02 | 0.1 |
| Lake and Partridge | | | | |
| PL ($\lambda$ = 0.9 cm, D = 11 m) | $\leqslant$ 0.2 | 0.02 | 0.002 | 0.01 |

[1]This table is reproduced from Rudnick (1978) with his permission.

sources are less intense at short wavelengths, so that our observations were less troubled by radio emission from sources within or near the clusters. Second, confusion is less a problem. The final advantage of shorter wavelength measurements is that thermal bremsstrahlung can be neglected.

Observations at short wavelengths present two problems, however. For a 2.8°K blackbody spectrum, $\lambda$ = 9 mm is not truly in the Rayleigh-Jeans region. The antenna temperature at 31.4 GHz is only 2.1°K, and it is only for antenna temperature that $\Delta T/T = \Delta I/I$. This loss in sensitivity, however, is partially compensated by the increase in magnitude of the function $f(x)$ in equation 1. A more fundamental difficulty is that receivers are noisier and the atmosphere is more emissive at 9 mm than at centimeter wavelengths. These are expected to be sources of statistical error, and we preferred to accept the possibility of larger statistical errors to avoid sources of possible systematic errors. The details of our observational technique and subsequent analysis are presented in a paper recently submitted to the Astrophysical Journal (Lake and Partridge, 1979).

Part way through our runs, we discovered two instrumental effects which produced spurious differences of a few millidegrees (mK) in antenna temperature. The first was a sudden jump in measured values of $\Delta T$ as the telescope crossed meridian <u>if</u> the transit occurred at high elevations. We have therefore excluded <u>all</u> data taken at elevations above 65°. The second effect was an elevation-dependent offset in the switched signal ("on" minus "off") which was present for sources in <u>some</u>, but not all, ranges of declination. Since we were not able to determine the origin of these offsets, we made extensive observations of nominally blank sky at the same declinations and over the same hour angles as our cluster observations. Finally we note that the elevation-dependent effect was particularly strong at $\delta \simeq 66°$ and is responsible for the large, and probably erroneous, negative temperature offsets reported by Lake and Partridge (1977) for Abell clusters 2125 and 2218, both of which lie near $\delta = 66°$. The magnitude of the effect is quite large, but data taken during different days and runs yield the same results, giving us confidence that we have been able to remove this systematic effect.

One must further make the various corrections for telescope efficiency, thermal bremsstrahlung and the geometry of the beam. This last correction is due to the non-filling of the main beam and the attenuation due to beam-switching in the nearby clusters which have an extent comparable to the size of the beam throw. Since this correction clearly depends on a model for the spatial extent and temperature run of the gas, it has not been made to the data appearing in Table 2.

The major conclusion of this work is that we find no reliable and significant evidence for the Sunyaev-Zel-dovich cooling in any of the clusters we observed, except for Abell 576.

TABLE 2

Brightness Temperature in mK for the Clusters Observed to Date

| Source | Lake and Partridge | Perrenod and Lada | Birkenshaw *et al.* | Rudnick |
|---|---|---|---|---|
| 376 | 1.86 ± 0.78 | | 1.61 ± 0.33 | |
| 401 | | | | -0.4 ± 0.4 |
| 426 | 3.67 ± 1.12 | | | |
| 478 | | | 0.54 ± 0.57 | |
| 506 | | 0.63 ± 0.76 | | |
| 518 | | -1.56 ± 0.83 | | |
| 545 | 1.68 ± 0.45 | | | |
| 576 | -1.27 ± 0.28 | | -0.70 ± 0.19 | |
| 665 | -1.03 ± 0.69 | -1.30 ± 0.59 | 0.32 ± 0.35 | |
| 777 | -0.22 ± 0.45 | | | |
| 910 | 0.22 ± 0.54 | | | |
| 1472A | | 1.24 ± 0.52 | | |
| 1472B | | -1.26 ± 1.02 | | |
| 1656 | 0.19 ± 0.22 | | 0.57 ± 0.53 | 0.4 ± 0.6 |
| 1656 (offset) | 0.07 ± 0.43 | | | |
| 1689 | -1.14 ± 0.88 | | | |
| 2079 | -0.04 ± 0.24 | | | |
| 2125 | 0.73 ± 0.45 | | 0.06 ± 0.30 | |
| 2142 | -0.47 ± 0.78 | | 0.41 ± 0.23 | |
| 2199 | | | | 0.6 ± 0.5 |
| 2218 Center | 0.80 ± 0.39 | -1.04 ± 0.48 | -1.09 ± 0.28 | |
| East | | -0.56 ± 0.73 | | |
| West | | -0.17 ± 0.68 | | |
| 2255 | | | | 0.7 ± 1.2 |
| 2319A | -0.06 ± 0.20 | 1.37 ± 0.94 | 0.25 ± 0.28 | 0.8 ± 0.9 |
| B | | 3.09 ± 1.61 | 0.98 ± 0.32 | |
| 2645 | 2.35 ± 0.71 | | | |
| 2666 | 0.63 ± 0.32 | | 0.33 ± 0.29 | |

## III. COMPARISONS AND CRITICISMS

Examining Table 2 we find a larger number of significant positive signals than negative ones. This should not destroy one's faith in the reality of the negative signals. Any source located at the center of the cluster produces a positive signal. However, since our telescope beam-switches in azimuth, the reference beam traces arcs about the cluster center. As a result, any source in the reference beam is only seen for a fraction of the total observing time and our method of analysis should detect its effect. This is also true for PL and BGN, but not for Rudnick who uses a telescope with a beam-switch in hour angle.

If we look across the columns of Table 2, we note a discrepancy in the case of A2218. This may be due to a difference in the source position used by us and the other groups. We used the position given by Abell (1958), whereas BGN have redetermined the position and obsere 1!5 to the North (roughly our halfpower beam width). PL also used the position of BGN.

If we look down the columns of Table 2, we see that half of the measurements of PL are roughly 2 $\sigma$ from zero (3 negative and 2 positive out of 10). For BGN, 5 out of 11 are also $\gtrsim$ 2 $\sigma$ from zero (2 negative and 3 positive). In our results, 6 out of 17 are $\gtrsim$ 2 $\sigma$ from zero (5 positive and 1 negative). In our observations, I think that 545 and 2645 might well be spurious. These sources are both at $\delta \approx -10°$ and show roughly the same signal. We did not have good blank sky coverage here and because of their low declination the elevation changes very little during our observations and the systematic is more difficult to determine. This is being explored in more detail. I have no reason to suspect the other three significant results we claim, but it is certainly reasonable to suspect that some non-gaussion process may be at work.

## IV. OUR GENERAL CONCLUSIONS

Only four of the 16 clusters we observed has a measured value of $\Delta T$ which can be more negative than -1 mK (sky or brightness temperature) at the 2 $\sigma$ level. Since the clusters we surveyed have a wide range of X-ray luminosity, velocity dispersion, richness and cluster core radius, our limits on the microwave decrement may be helpful in constraining models for the origin and distribution of intergalactic plasma in clusters. The constraints on some well observed clusters, such as A777, A1656, A2079, A2125 and A2319, are particularly tight.

In general, we will leave to others detailed comparisons of our results with the theoretical models. We would, however, like to make three general points concerning our results.

First, it is clear that the apparent correlation we noted in 1977 (Lake and Partridge) between cluster richness and the size of $\Delta T$ is not supported by these further studies. The apparent correlation we reported was based on observations of three richness class 4 clusters; we now know that the values for $\Delta T$ reported for two of them were erroneous, because of the systematic effect mentioned in section II.ii. Our present work shows no significant correlation between $\Delta T$ and richness. This is in accord with the work of Pravdo, et al. (1979) who find no positive correlation between the richness of a cluster and its thermal bremsstrahlung X-ray emission.

Next, we note that of the roughly 20 clusters observed by us or by other groups, only two - numbers A576 and A2218 - are reported to have a significant decrement. Why have we (and others) not detected the Sunyaev-Zel-dovich effect in other clusters? Our failure to detect a microwave decrement, especially in clusters known to be X-ray sources such as A2079 and A2319, may indicate that bremsstrahlung emission from cooler gas is masking the inverse Compton cooling (Tarter 1978). Such emission could help explain some of our positive values of $\Delta T$. It may also be that the so-called clumping factor $\langle n_e{}^2\rangle/\langle n_e\rangle^2$ is substantially greater than unity. If the latter is the case, our results favor models where the hot gas is physically clumped; or more probably models with a high central concentration (which raises $\langle n_e{}^2\rangle/\langle n_e\rangle^2$ averaged over the cluster), rather than those with a more uniform distribution of gas. High resolution X-ray studies by HEAO-2 may help resolve this issue.

Further, since the X-ray flux varies as $T^{1/2}$, whereas the microwave decrement varies as T, decreasing the temperature with a fixed X-ray flux results in a smaller expected diminution. In the case of A576 White and Silk (private communication, 1979) are finding a temperature of $\sim 10^7$°K rather than $10^8$°K. This particular case is rather embarrassing, since it is the one cluster for which we claim to detect the effect. Studies of silicon and magnesium lines with the crystal spectrometer aboard HEAO-2 will provide much more reliable temperatures.

One is still left with the question: why does A576, and possibly A2218 (Birkinshaw, et al. 1978b), show a microwave decrement? Since many other comparable clusters do not appear to produce a significant cooling, it is reasonable to ask what is special about these two? Neither is an especially luminous X-ray source. Neither differs in richness or morpohology from other clusters we have observed.

The questions raised in the previous sections brings us to our final point: caution should be used when these or other microwave measurements are used to constrain theoretical models, or to determine the Hubble constant.

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## DISCUSSION

*Jaffe:* Could some of the scatter in your data be due to the first-order Doppler effect from a large amount of cool gas surrounding the cluster and moving with some peculiar velocity?

*Lake:* My first thought is that bremmstrahlung would be stronger. Second, how is such a cool gas supported?

*Peebles:* Have you computed the correlation coefficients among the independent sets of measurements of $\delta T/T$ for each cluster?

*Lake:* No, I have not. Part of the problem with such a comparison can be seen in Table 1. The contribution of radio sources is quite different at the three frequencies that have been observed.