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A search for cold dust in clusters of galaxies with cooling flows

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ABSTRACT

We report a submillimetre-wavelength search for thermal emission from cold dust in the centres of rich clusters of galaxies with cooling flows. No convincing example of emission by dust is found in the 11 clusters surveyed. The upper limits to the dust mass are of order $10^8\,M_\odot$. The corresponding limits to the mass of cold gas are of order $10^{10}\,M_\odot$, assuming the Galactic ratio of gas to dust mass.

Key words: dust, extinction – galaxies: clustering – cooling flows – radio continuum: galaxies.

1 INTRODUCTION

Most rich clusters of galaxies have a thermally supported atmosphere of 10^8 K plasma (e.g. Sarazin 1988). This plasma produces an X-ray surface brightness distribution that is often centrally peaked. Analysis of the central peaks suggests that the X-ray emission cools the plasma in less than a Hubble time, and that this cooling in turn drives mass accretion rates of 10–$100\,M_\odot\,yr^{-1}$ (Fabian 1988, and references therein). The average cooling flow should, over a Hubble time, deposit 10^{11}–$10^{12}\,M_\odot$ of cooled material at the base of the flow.

The central mystery of cooling flows remains the fate of the cooled material. There are several lines of evidence to suggest that the plasma is indeed cooling down from 10^8 K (e.g. Johnstone et al. 1992), but the cooled material does not seem to be forming into stars, as the derived star formation rates ($\leq 1\,M_\odot\,yr^{-1}$, e.g. McNamara & O'Connell 1992) are very much less than the accretion rates. Nor does the cooled material seem to be collecting into a neutral pool at the base of the flow, as surveys for neutral hydrogen and molecular gas find upper limits of 10^9–$10^{10}\,M_\odot$ (e.g. McNamara, Bregman & O'Connell 1990; McNamara & Jaffe 1993). Various ways to hide the material have been proposed. A currently popular scenario is that the cooled material resides in cold dense clouds. The report of excess absorption in the soft X-ray spectrum of cooling flow clusters (White et al. 1991) suggests such a scenario. If the observation is confirmed, it requires high column densities of predominantly neutral gas. Depending on the distribution of the gas, the mass involved may be $\geq 10^{11}\,M_\odot$. Such large amounts of material may be hidden from the neutral hydrogen surveys if the material is collecting into a form optically thick to H I, such as the proposed cold, very dense clouds.

We test the dense cold cloud scenario by searching for the dust which is usually associated with cold gas. Previous searches for thermal emission by dust used *IRAS* 100-μm observations (Bregman, McNamara & O'Connell 1990, hereafter BMO; Grabelsky & Ulmer 1990). For our problem this approach has two limitations. First, the *IRAS* beam is large, and contamination by Galactic cirrus may be significant. Secondly, the likely dust temperature is $10 < T_d < 50$ K, so the *IRAS* 100-μm bandpass samples the Wien side of the Planck function, where estimates of the dust mass required to produce the observed flux depend sensitively on the assumed dust temperature (Draine 1990). For example, BMO found that their estimated dust mass was proportional to $T_d^{-5.9}$, so a factor of 2 error in their assumed T_d gives rise to a factor of 60 error in the derived mass. We choose to minimize these difficulties by observing at high spatial resolution in the submillimetre, and hence on the Rayleigh–Jeans side of the dust thermal emission. Throughout this paper we use $H_0 = 75$ km s^{-1} Mpc^{-1}.

2 OBSERVATIONS

We observed at the 15-m James Clerk Maxwell Telescope (JCMT), located on Mauna Kea in Hawaii. We used the liquid ^{3}He bolometer system UKT-14 (Duncan et al. 1990), with 0.8- and 1.1-mm filters, and a 65-mm circular aperture. The diameters of the beams projected on the sky were 16.5 arcsec FWHM at 0.8 mm and 18 arcsec FWHM at 1.1 mm. In order to remove the contributions of the telescope and the rapidly varying sky, the secondary mirror was chopped at a frequency of 7.8 Hz, with a throw in azimuth of either 60 arcsec (A1126, A1795 and A2319) or 120 arcsec

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(all other clusters). After each 10-s observation, the throw was changed to the opposite side of the object to avoid possible systematic effects of chopping to one side only. An example of the positioning of the object and sky beams is shown in Fig. 1. In order to ensure the accuracy of the JCMT pointing, bright sources of known position near each cluster were observed before and during each cluster observation. Generally, the pointing was found to be accurate to better than 2 arcsec. In addition, the bright source observations provided a means of monitoring the atmospheric opacity.

We selected 11 clusters on the basis of redshift, cooling rate, and the availability of reliable positions. Since the base of the cooling flow is always located in a large central galaxy and many of these galaxies exhibit emission-line complexes indicative of cooling gas (Hu, Cowie & Wang 1985), we chose to observe the centres of the central cluster galaxies. We prefer the positions from Burns (1989) and Zhao, Burns & Owen (1989), as they report how the coordinates were determined and to what accuracy. Table 1 gives the coordinates at which we observed, the reference for those coordinates, and a reference to an alternative position when available. Table 1 shows that the coordinates of A644 and A2029 are discrepant by one or more beam radii, so the data for these clusters must be used with caution.

During our first run, 1992 May 2–6 UT, the atmospheric conditions allowed us to observe exclusively at 0.8 mm. On our second run, 1992 August 2–6 UT, poorer atmospheric conditions forced us to observe primarily at 1.1 mm. We employed Jupiter as our primary standard on the first run, and both Jupiter and Uranus on our second run. We assumed the flux density from Jupiter to be 4964 Jy at 0.8 mm on May 6, and 2970 Jy at 1.1 mm on August 4, and the flux from Uranus to be 50.7 Jy at 1.1 mm on August 4. The measured flux densities and associated errors are reported in Table 2.

3 THE ESTIMATION OF DUST MASS

We assume that the dust is optically thin to submillimetre radiation. The observed flux density, S_ν, may then be used to make an estimate of the dust mass M_d from

$$M_\mathrm{d} = \frac{S_\nu}{B_\nu(T)} \frac{d_\theta^2}{\kappa(\lambda_\mathrm{e})},$$

where $B_\nu(T)$ is the observed Planck blackbody spectrum, d_θ is the angular-diameter distance, $\kappa(\lambda_\mathrm{e})$ is the opacity of the dust in the rest frame of the dust, and T is related to the dust temperature by $T_\mathrm{d} = (1+z)T$. We note that, in the Rayleigh–Jeans limit, $M_\mathrm{d} \propto T^{-1}$.

The primary uncertainty in submillimetre mass determinations is the dust opacity. We use

$$\kappa(\lambda) = \frac{0.1}{\lambda^n} \frac{m^2}{kg}$$

(dust mass only), where λ is the wavelength in mm. This value for $\kappa(\lambda)$ is in the middle of the currently acceptable range at $\lambda = 1.0$ mm (Draine 1990). Here n represents the

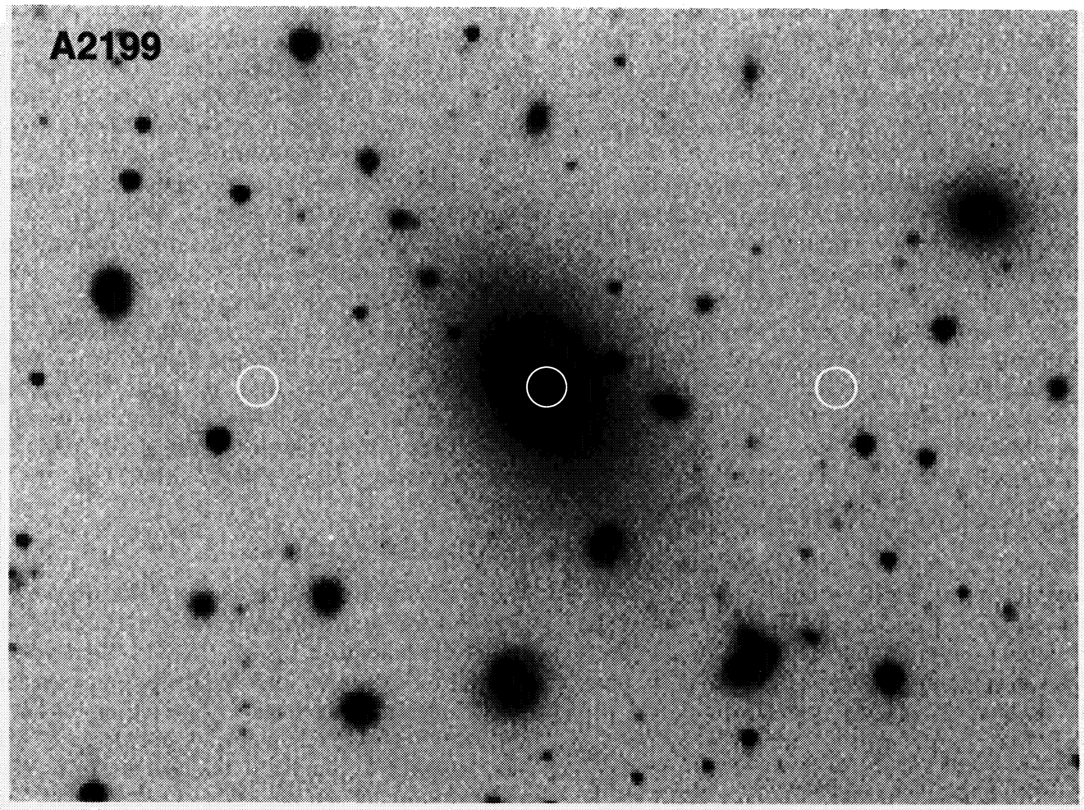

Figure 1. The positions and sizes of the UKT-14 photometry and sky reference apertures superimposed on an optical (R-band) image of the A2199 cluster.

Table 1. Cluster coordinates.

Cluster	$\alpha(1950)$	$\delta(1950)$	Reference	Alternative Ref.	$\Delta\theta$
A644	$08^h\ 15^m 00^s$	$-07°\ 21'\ 22''$	Hu et al. 1985	Burns 1989	11″
A978	10 17 56	−06 16 27	Hu et al. 1985	...	...
A1126	10 51 10	+17 06 35	Hu et al. 1985	...	...
A1795	13 46 34	+26 50 28	Hu et al. 1985	Burns 1989	4″
A2029	15 08 27	+05 56 35	Hu et al. 1985	Burns 1989	38″
A2052	15 14 17	+07 12 17	Tonry 1985	Zhao et al. 1989	1″
A2063	15 20 39	+08 47 12	McNamara et al. 1990	Tonry 1985	2″
A2199	16 26 57	+39 40 31	Burns et al. 1983	...	...
A2319	19 19 36.7	+43 51 00	Burns 1989	...	...
A2626	23 33 59.3	+20 52 11	Zhao et al. 1989	...	...
A2670	23 51 39.6	−10 41 52	Burns 1989	...	...

Table 2. Submillimetre continuum observations.

Cluster	1992 Date	$\lambda[mm]$	$S_\nu[mJy]$	$\sigma[mJy]$
A644	May 3	0.8	-3	8
A978	May 4,6	0.8	-17	7
A1126	May 2	0.8	-11	5
A1795	May 2	0.8	-1	8
A2029	May 6	0.8	-12	7
A2052	Aug 5	1.1	51	9
A2052	Aug 5	0.8	58	20
A2063	May 3	0.8	-9	6
A2199	Aug 4,5	1.1	16	5
A2319	Aug 2,3,4	1.1	3	4
A2626	Aug 6	1.1	-10	8
A2670	Aug 5	1.1	2	6

Table 3. Derived limits on dust mass.

Cluster	z	$\dot{M}$ [$M_\odot yr^{-1}$]	3σ [mJy]	M_d [$M_\odot$]	Beam [kpc]
A644	0.0781	139	24	$\lesssim 1.6\times10^8$	24
A978	0.0527	222	21	$\lesssim 7.2\times10^7$	17
A1126	0.0831	222	15	$\lesssim 1.1\times10^8$	26
A1795	0.0621	144	24	$\lesssim 1.1\times10^8$	20
A2029	0.0767	156	21	$\lesssim 1.4\times10^8$	24
A2052	0.0345	54	60	$\lesssim 9.2\times10^7$	11
A2063	0.0337	12	18	$\lesssim 2.6\times10^7$	11
A2199	0.0305	38	15	$\lesssim 6.8\times10^7$	10
A2319	0.0529	33	12	$\lesssim 1.4\times10^8$	17
A2626	0.0554	12	24	$\lesssim 3.2\times10^8$	18
A2670	0.0774	0	18	$\lesssim 4.4\times10^8$	24

Notes: Column (3) lists the cooling flow mass deposition rate, from Heckman et al. (1989). Column (5) lists the 3σ upper limits to the dust mass present, derived assuming $H_0=75$ km s^{-1} Mpc^{-1} and $q_0=0.1$. In the case of A2199, the limit is actually a detection of the radio source, but is therefore also a limit to the dust present. In the case of A2052, the 800-μm flux upper limit was used to derive the mass limit. Column (6) lists the physical size subtended by the beam of the JCMT.

unknown emissivity index of the dust. To estimate masses from the 0.8- and 1.1-mm fluxes, we have used $n=1$. As both wavelengths of observation are close to 1.0 mm, the uncertainty caused by n is negligible.

The temperature of the dust is not well known. Dwek, Rephaeli & Mather (1990) calculate that collisional heating of dust by high-energy electrons in the X-ray gas will cause the dust to attain an equilibrium temperature $T_d \approx 20$ K. If the dust resides instead in clouds that are optically thick to high-energy electrons, the dust will be colder. Loewenstein & Fabian (1990) calculate that in such clouds heating by hard X-rays and cosmic rays produces $T_d \approx 10$ K.

The resulting 3σ upper limits to the mass present are given in Table 3, for an assumed $T_d=20$ K. The limits would be increased by a factor of 3 if $T_d=10$ K, and lowered by a factor of 2 if $T_d=30$ K. We note that our limits refer to the dust present within our 16–18 arcsec diameter beam, and that our survey is insensitive to dust with spatial distribution scales larger than ≈ 100 kpc due to our chopping arrangement.

4 THE MASS OF DUST IN CLUSTER CENTRES

We find no evidence for thermal emission by dust at the bases of cooling flows. The upper limits to the dust masses range from $M_d \lesssim 3\times10^7$ to $M_d \lesssim 4\times10^8$ $M_\odot$, averaging about $M_d \lesssim 10^8$ $M_\odot$. For the Galactic value of the gas-to-dust ratio, 157, this value corresponds to a gas mass $M_g \lesssim 2\times10^{10}$ $M_\odot$. These upper limits are comparable to both neutral hydrogen and molecular gas upper limits and detections (McNamara et al. 1990; Grabelsky & Ulmer 1990). There is no evidence for the required 10^{11}–10^{12} $M_\odot$ of material deposited by the cooling flow.

We detected submillimetre emission from A2052 and A2199 (see Table 2). In each of these cases, the detected flux was consistent with that expected from the high-frequency tail of the emission from the bright radio source in the central galaxy. In particular, the detection of A2052 at 1.1 mm but not at 0.8 mm is inconsistent with the steeply rising spectrum expected from thermal emission by dust.

The detections of cool dust in the central cluster galaxies by BMO and Grabelsky & Ulmer (1990) are consistent with the upper limits in Table 3. We illustrate this by considering the measurements of three clusters for which BMO report infrared emission: A1126, A2063 and A2670. The temperature of the dust may be estimated by using the Planck function to compare observed fluxes at two different wavelengths. BMO found that the average 100- to 60-μm flux ratio for these three clusters implies $T_d \approx 30$ K. Our measured 0.8- and 1.1-mm flux upper limits, when expressed as a ratio to the *IRAS* 100-μm fluxes, imply $T_d > 20$ and $T_d > 35$ K, for $n=2$ and $n=1$ respectively. The two data sets are in agreement for $T_d \approx 30$ K. It should, however, be borne in mind that the JCMT and *IRAS* have very different beam-sizes. If the combined data set is taken at face value, and if the *IRAS* detections are not due to cirrus, the relative fluxes suggest that these central cluster galaxies have $M_d \leq 10^8\,M_\odot$ and $T_d \geq 30$ K.

The use of the limits in Table 3 for testing the dense cold cloud hypothesis depends on the assumed gas-to-dust mass ratio. We adopt the Galactic value, as it is not clear how the putative dense cold clouds would differ from Galactic molecular clouds. A useful construct is the accumulation time, $t_a \sim M_g/\dot{M}$, where $\dot{M}$ is the mass accretion rate, and M_g is our derived upper limit to the presence of cold gas. The data presented in Table 3 give $t_a \leq 10^8$–10^9 yr. If the dust is distributed through the X-ray-emitting region, it has a life-span against sputtering by X-rays of 10^7–10^8 yr, comparable to or shorter than our limits. The dense cold cloud scenario, however, requires the clouds to be optically thick to H I in order to avoid violating the H I upper limits. Such clouds would probably be optically thick to X-rays, thus shielding the dust from sputtering and dramatically increasing the dust life-span. In such a case, our limits correspond to less than a billion years of accretion, which in turn suggests that, at most, a small fraction of the material from the cooling flow can be hidden in clouds of this form.

It is instructive to compare our observations with those of radio galaxies. The measured dust mass limits for the central cluster galaxies are comparable to both the detections of dust and upper limits to dust in radio galaxies (Knapp & Patten 1991), suggesting that there is no more dust in central cluster galaxies than in radio galaxies. The *IRAS*-derived, far-infrared luminosities for central galaxies are, for a given *B* magnitude, a factor of 10 higher than for radio galaxies (BMO; Knapp, Bies & van Gorkom 1990). This is easily attributable to the sensitivity of Wien-side measurements, where a 50 per cent increase in T_d can lead to a factor of 10 increase in flux density. Instead of showing the effects of the presence of a rich cluster of galaxies, the observations suggest a similarity between the far-infrared properties of radio galaxies and central cluster galaxies.

5 CONCLUSIONS

We have searched for thermal emission by cold dust in the centres of clusters of galaxies with cooling flows. The sub-millimetre wavelengths employed are sensitive even to very cool dust, and provide dust mass estimates that are relatively insensitive to the adopted dust temperature. We find no convincing case of thermal emission by dust in the 11 clusters surveyed. The 3σ upper limits to the dust mass are of order $10^8\,M_\odot$. The implied limits to gass mass are of order $10^{10}\,M_\odot$, in agreement with the limits to the presence of cold material from neutral hydrogen and molecular CO surveys, but are, like the CO limits, dependent on the Galactic calibration. In particular, we find no evidence for the 10^{11}–10^{12} $M_\odot$ of cold material required by the cold, dense, optically thick cloud scenario.

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REFERENCES

Bregman J. N., McNamara B. R., O'Connell R. W., 1990, ApJ, 351, 406 (BMO)
Burns J. O., 1989, AJ, 99, 14
Burns J. O., Schwendeman E., White R. A., 1983, ApJ, 271, 575
Draine B. T., 1990, in Thronson H., Shull J., eds, The Interstellar Medium in Galaxies. Kluwer, Dordrecht, p. 483
Duncan W. D., Robson E. I., Ade P. A., Griffin M. J., Sandell G., 1990, MNRAS, 243, 126
Dwek E., Rephaeli Y., Mather J. C., 1990, ApJ, 350, 104
Fabian A. C., 1988, in Fabian A., ed., Cooling Flows in Clusters and Galaxies. Kluwer, Dordrecht, p. 315
Grabelsky D. A., Ulmer M. P., 1990, ApJ, 355, 401
Heckman T. M., Baum S. A., van Breugel W. J. M., McCarthy P., 1989, ApJ, 338, 48
Hu E., Cowie L., Wang Z., 1985, ApJS, 59, 447
Johnstone R. M., Fabian A. C., Edge A. C., Thomas P. A., 1992, MNRAS, 255, 431
Knapp G. R., Patten B. M., 1991, AJ, 101, 1609
Knapp G. R., Bies W. E., van Gorkom J. H., 1990, AJ, 99, 476
Loewenstein M., Fabian A. C., 1990, MNRAS, 242, 120
McNamara B. R., Jaffe W., 1993, preprint
McNamara B. R., O'Connell R. W., 1992, ApJ, 393, 579
McNamara B. R., Bregman J. N., O'Connell R. W., 1990, ApJ, 360, 20
Sarazin C. L., 1988, X-ray Emissions from Clusters of Galaxies. Cambridge Univ. Press, Cambridge
Tonry J., 1985, AJ, 90, 2431
White D. A., Fabian A. C., Johnstone R. M., Mushotzky R. F., Arnaud K. A., 1991, MNRAS, 252, 72
Zhao J., Burns J. O., Owen F. N., 1989, AJ, 98, 64