The detection of dust in the central galaxies of distant cooling-flow clusters

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ABSTRACT
We present 850-µm observations with the SCUBA submillimetre (sub-mm) camera of the central galaxies in seven concentrated clusters of galaxies at redshifts between 0.19 and 0.41. We detect sub-mm emission from the central galaxies in the rich clusters A 1835 and A 2390, and present upper limits for the central galaxies in the remaining five clusters. The two galaxies which we detect both exhibit unusually blue UV-optical colours and lie in clusters which contain massive cooling flows, \( \geq 1000 \, M_\odot \, yr^{-1} \). Moreover, both galaxies host relatively strong radio sources. Focusing on these two systems, we present new and archival radio—optical observations to provide a detailed view of their spectral energy distributions. Our analysis indicates that sub-mm emission from the central galaxy of A 1835 can be best understood as arising from dust, heated either by vigorous star formation or an obscured active galactic nucleus. For the central galaxy of A 2390, the sub-mm flux is marginally consistent with an extrapolation of the centimetre–millimetre emission from the luminous radio source that lies in its core; although we cannot rule out an excess flux density from dust emission comparable to that seen in A 1835. We present details of our multi-wavelength observations and discuss the implications of these data for the interpretation of star formation in cooling-flow galaxies.

Key words: galaxies: active — galaxies: starburst — galaxies: cooling flow — galaxies: individual: A 1835, A 2390 — X-ray: cooling flow

1 INTRODUCTION

The cooling time of hot X-ray-emitting gas in the central regions of massive, relaxed clusters of galaxies can be substantially less than the Hubble time. The gas in these regions can thus cool and recombine, initiating a cooling flow (Fabian & Nulsen 1977; Cowie & Binney 1977). The ultimate fate of this cooling gas has been the subject of an extensive and strongly contested debate (see Fabian 1994). The cold gas is not detected in molecular form and so is inferred to reside in a phase with \( T_{\text{gas}} \ll 100 \, \text{K} \). Calculations of the gas properties are consistent with current observed limits (Fordland, Fabian & Johnstone 1994). The metals in this cold and probably dense gas are likely to condense to form dust grains, although the lifetime of these grains could be severely limited due to sputtering from the X-rays emitted by the surrounding hot gas in the cluster core.

Observations of the central cluster galaxies in cooling-flow clusters indicate that large numbers of stars are not formed from the reservoir of cold gas created by the cooling-flow, although it has been suggested that the initial mass function may be biased in favour of low-mass stars so that the integrated stellar spectrum is difficult to detect (Fabian, Nulsen & Canizares 1982). However, many cooling-flow clusters contain optical emission-line nebulae around their central galaxies, on scales of up to 100 kpc, and their emission-line ratios (assuming Case B recombination) suggest that considerable amounts of dust may be present in the central regions of these clusters obscuring any stars formed there (Hansen, Jørgensen & Nörgaard-Nielsen 1995; Allen 1995). Dust has also been inferred from direct detection of dust lanes in recent Hubble Space Telescope (HST) imaging of central cluster galaxies (e.g. A1795, McNamara et al. 1996; Pinkney et al. 1996). However, it is difficult to quantify the total mass or temperature of this dust from the observations, although the dust mass implied could be substantial enough to obscure any young, blue stars being formed from the cooling-flow gas. The origin of the dust seen in these
Table 1. The properties of the clusters in the sub-mm survey.

| Cluster     | z       | α (J2000) | δ (J2000) | t1 (ks) | S_{500\mu m} (mJy) | L_{2_{K}}^\dagger (erg s^{-1}) | T_{X}^2 (keV) | M^3 (M_\odot yr^{-1}) | Comments               |
|-------------|---------|-----------|-----------|---------|--------------------|-------------------------------|-------------|------------------|----------------------|
| Cl10024+16 | 0.39    | 00^h26^m35.80^s | +17^\circ09'41.0'' | 15.6    | < 8.7              | 2.0 × 10^{44}                | ...          | 96 +90/−53       | Multiple gE          |
| A 370       | 0.37    | 02^h39^m53.18^s | −01^\circ35'58.0'' | 33.8    | < 5.4              | 1.6 × 10^{45}                | 7.2 +1.0/−0.8 | < 97 Southern D  |
| MS 0440+02  | 0.19    | 04^h43^m10.08^s | +02^\circ10'18.0'' | 35.8    | < 3.9              | 3.9 × 10^{44}                | 5.3 +1.3/−0.9 | 65 +103/−40       | Multiple gE          |
| A 851       | 0.40    | 09^h12^m56.68^s | +46^\circ59'09.0'' | 30.1    | < 5.0              | 6.8 × 10^{44}                | 6.7 +2.1/−1.7 | < 46 Two D gals  |
| A 1835      | 0.25    | 14^h01^m02.11^s | +02^\circ52'43.1'' | 23.0    | 4.0 ± 1.2          | 4.5 × 10^{45}                | 9.8 +2.3/−1.3 | 1760 ±520/590   | cD galaxy            |
| A 2390      | 0.23    | 21^h53^m36.76^s | +17^\circ41'44.2'' | 33.7    | 9.9 ± 1.74         | 4.1 × 10^{45}                | 14.5 +15.5/−5.2 | 1530 ±560/1110 | cD galaxy            |
| Cl 2244−02  | 0.33    | 22^h47^m12.37^s | −02^\circ05'44.0'' | 25.6    | < 6.0              | 1.3 × 10^{44}                | ...          | < 40    Multiple gE |

1) Exposure time of the 850-μm SCUBA maps.
2) 2–10-keV X-ray luminosity and temperature (Mushotzky & Scharf 1997; Allen 1998).
3) Mass deposition rate in the cooling flow from X-ray spectroscopy (Allen 1998) for A1835 and A2390. Mass deposition rates for all other clusters derived from archival ROSAT imaging data using a deprojection code (see White, Jones & Forman 1997).
4) Confirmed by a photometry-mode SCUBA observation at 850 μm: 9.8 ± 2.0 mJy; weighted mean: 9.9 ± 1.3 mJy.

galaxies is still an open issue, it could either originate from the cooled gas clouds themselves or from the on-going star formation. Unfortunately, it is difficult to observationally distinguish between these two scenarios.

A direct detection of dust in cooling-flow galaxies and a more robust estimate of its total mass and temperature would provide a substantial insight into the physical processes occurring in the cooling-flow gas (e.g. Fabian, Johnstone & Daines 1994). For the temperatures inferred for dust in cooling flows (< 40 k, see O’Dea et al. 1994), the dust will radiate predominantly in the sub-mm waveband; effort has therefore been invested in obtaining a direct confirmation of the presence of dust in cooling-flow galaxies using the UKT14 bolometer on the James Clerk Maxwell Telescope (JCMT) at 850 and 1100 μm. Observations of 11 central galaxies in cooling-flow clusters at z < 0.1 were undertaken by Annis & Jewitt (1993). All detections were compatible with an extrapolation of the centimetre-wave radio emission associated with the central cluster galaxies, but these observations were able to set useful limits on the total mass of dust in the central 10 kpc of these systems: < 10^7 M_\odot. The only nearby cooling flow with a sub-mm detection is that around NGC 1275 in Perseus (Gear et al. 1985; Lester et al. 1995), although the interpretation in this source is complicated by the strongly varying nuclear component. Moreover, the presence of the dust may be related to apparently ongoing galaxy merger in this system, which has been the subject of a long-running debate (Van den Bergh 1977; Hu et al. 1983; Pedlar et al. 1990; Holtzman et al. 1992; Nørgaard-Nielsen et al. 1993).

In the far-infrared the Infrared Astronomical Satellite (IRAS) detected a number of central cluster galaxies (Bregman, McNamara & O’Connell 1990; Grabelsky & Ulmer 1990; Wise et al. 1993; Cox, Bregman & Schombert 1995). Although the number of detections was small and foreground and background contamination effects make it difficult to draw conclusions as to the presence of dust in individual central cluster galaxies, Cox et al. (1995) conclude that up to 10 per cent of clusters contain a central cluster galaxy with 10^7 M_\odot of dust. At higher redshifts, IRAS detected the central galaxy in a cooling-flow cluster at z = 0.44, IRAS09104+4109 (Kleinmann et al. 1988; Fabian & Crawford 1995), although this is likely to host an obscured quasar nucleus (Hines & Wills 1993). Thus a conservative summary of previous sub-mm observations of cooling-flow galaxies is that all are ambiguous as a result of modest sensitivity and/or strong contamination from non-thermal emission.

With the introduction of sensitive bolometer cameras operating in the sub-mm, in particular the Submillimetre Common-User Bolometer Array (SCUBA) on the JCMT (Holland et al. 1999), our ability to detect emission from cold dust has been greatly enhanced. In this paper we discuss sub-mm observations of seven distant, concentrated galaxy clusters at z = 0.19–0.41. These were observed as part of a deep sub-mm survey of the distant Universe (Small, Ivison & Blain 1997; Small et al. 1998a) which we briefly review in §2. The deep maps obtained at 850 μm have detected emission associated with the central galaxies of two of the clusters, A 1835 (z = 0.23) and A 2390 (z = 0.25), and to place upper limits on the emission from the remaining five central galaxies. In §3 and §4, we combine our sub-mm data for the central galaxies in A 1835 and A 2390 with new and archival observations in the radio, infrared (IR) and optical wavebands, providing a view of their spectral energy distributions across a wide wavelength range. We discuss our results and then give our conclusions in §5. Throughout we assume Ω_0 = 1 and H_{0} = 50 km s^{-1} Mpc^{-1}.

2 THE SCUBA SURVEY OF LENSING CLUSTERS

The deep 850-μm maps analysed in this work were obtained in a survey of the distant Universe as seen through foreground galaxy clusters. Data were obtaining during several observing sessions in 1997 and 1998. The survey concentrated on massive, lensing clusters to take advantage of the gravitational amplification of all background galaxies.

The survey resulted in the discovery of a large population of distant star-forming galaxies, the properties of which
are discussed in Smail et al. (1997, 1998a, 1999), Ivison et al. (1998, 1999), Blain et al. (1999a, 1999b) and Barger et al. (1999). Those papers also provide details of the acquisition, reduction and analysis of the 850-µm maps and the identification of the optical counterparts of the sub-mm sources. In Table 1, we list the clusters, the exposure times and the flux densities of the central galaxies measured in 30-arcsec-diameter apertures (∼120–200 kpc at the cluster redshifts), or 3-σ upper limits. We have adopted a fixed metric aperture for the flux measurement to accomodate the possibility of extended dust emission in the cluster core. Smail et al. (1998a) review the likelihood of each sub-mm source having a counterpart in deep optical images. For the two detections presented here, the brightest cluster galaxy is the most probable counterpart and any offset between the sub-mm source and galaxy positions is consistent with the combined astrometric accuracy of the SCUBA maps and the signal to noise of the detected source.

Only two of the clusters in the survey show detectable 850-µm emission from their central galaxies: A 1835 and A 2390. These galaxies lie in two of the most massive known cooling flows, both are sources of strong radio emission, and both exhibit strong optical emission lines (Allen et al. 1992; Le Borgne et al. 1991). The presence of substantial amounts of dust in A 1835 was suggested by the analysis of optical emission-line ratios by Allen (1995) who estimated an intrinsic reddening of \( E(B-V) = 0.49_{-0.12}^{+0.17} \). Correcting for this Allen estimated a star-formation rate from the Hα luminosity as high as 400 \( M_\odot \) yr\(^{-1} \). These levels of reddening (and therefore dust) and star formation would make this galaxy comparable to the most extreme starbursts.

The remaining five clusters do not show detectable 850-µm emission from their central galaxies. Due to modest atmospheric transmission the sensitivities of our 450-µm SCUBA maps do not provide interesting limits for these five clusters. None of these five clusters contains a large cooling flow (all have \( M < 100 M_\odot \) yr\(^{-1} \) see Table 1); only one – MS 0440+02 – is known to exhibit optical line emission (Donahue et al. 1992) or radio emission comparable to A 1835 or A 2390 (41.5 mJy at 1.4 GHz from NVSS Condon et al. 1998 which sets upper limits of 3 mJy for all other sources).

We note that neither of the two detected central galaxies are in the clusters originally analysed by Smail, Ivison & Blain (1997) and furthermore these sources have been removed from any subsequent analysis of sub-mm source counts (Blain et al. 1999a).

### 3 Observations of the Central Galaxies in A 1835 and A 2390

Here we review the available observations of the central galaxies in A 1835 and A 2390. These include further sub-mm observations, new and archival radio maps from the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA), as well as IR–optical photometry. The observations are summarised in Table 2. Before discussing these in detail we caution that the precise form of the spectral energy distributions (SEDs) of these galaxies are sensitive to the choice of aperture used in the different passbands. Unfortunately without full knowledge of the extent of the emission region as a function of wavelength it is difficult to remove such effects from observations across a wide range of wavelengths and with different resolutions. In what follows we have adopted the long wavelength measurements as total fluxes and corrected the observations in the near-infrared and optical to ‘total’ values assuming the aperture correction derived for the cD galaxies in the \( I \)-band. This scheme assumes that the published ISO fluxes in Lemonon et al. (1998) for A 2390 corrected in the manner discussed in that paper represent the total emission for this galaxy.

#### 3.1 Radio observations

During 1997 October 22, we observed the central radio source in A 2390 at frequencies between 1.4 and 43 GHz using the D configuration of the VLA. The data were reduced and analysed using standard AIPS procedures. In addition, we extracted three archival datasets from 1990 March 3, 1990 August 27 and June 1995 May 10 to test for variability. For the 1990 August dataset, presented by Lemonon et al. (1998), we found no reliable phase solutions for any of the high-frequency data at 15 and 22 GHz. The conclusions presented by Lemonon et al. (1998), based on these observations, are therefore likely to be inaccurate. Using the remaining observations, we find no compelling evidence for any variability of the nuclear component above the 10-per-cent level between 1990 and 1998.

The 1990 March and August data were obtained using the VLA in configurations A and B, respectively, and so have significantly higher resolution than the D-configuration maps from 1995 and 1997 (factors of 35 and 10 respectively). Most of the flux in the data from 1990 is resolved at 4.89 GHz into a \( 0.3'' \times 0.15'' \) component at a position angle of 44°. The higher spatial resolution data results in a lower integrated flux density, indicating that there is an extended component to the radio emission. This extended emission is also evident from the detection of the source in the Texas Survey at 365 MHz (Douglas et al. 1996), where the low-frequency tail of the second extended component exceeds the emission from the inverted nuclear source. This extended radio emission may be associated with a cluster halo, but more sensitive low-frequency observations are required to investigate this possibility.

For A 1835, the radio data listed in Table 2 came from a number of observing sessions with the VLA: the first, a 4.89-GHz map in C configuration on 1994 November 14; the second, 1.4- and 15-GHz maps in B configuration on 1997 February 13; the last, 1.4- and 8.4-GHz maps in A configuration on 1998 April 12. Data from Condon et al. (1998) and Cooray et al. (1998) were included to give frequency coverage comparable to A 2390. The wide variety of resolutions and frequencies results in some scatter in the derived flux densities, since there is some extended radio emission in this source on scales of 5–20''. However, most of the flux is in a compact (< 0.2'') component, similar to but less powerful than that in A 2390. Within the limitations of comparing the different resolution data, the source does not appear to be variable on timescales of a few years at a level required to significantly contribute to the sub-mm.
3.2 Further sub-mm observations

To supplement the detections of the central galaxies in A 1835 (450 and 850 µm) and A 2390 (850 µm) in our sub-mm maps, we obtained photometry-mode data using SCUBA (see Ivison et al. 1998 for details of photometry-mode observations and data reduction). Data were obtained at 1350 µm for A 1835 and at 450, 850, 1350 and 2000 µm for A 2390.

A 4-ks observation of A 1835 at 1350 µm was made under relatively poor conditions (with a noise-equivalent flux density of 105 mJy Hz$^{-1/2}$, nearly twice the nominal value) but we obtain a useful upper limit of 3σ < 4.9 mJy.

Observations of A 2390 were made in excellent conditions. In total exposure times of 0.9 and 1.8 ks we obtained robust detections of the emission from the central galaxy at 1350 and 2000 µm respectively. At 450 and 850 µm, a 1.8-ks exposure in photometry mode confirmed the photometric accuracy of the relevant Smail et al. (1999) maps. The weighted mean 850-µm flux density is 9.9 ± 1.3 mJy. The 450-µm upper limit (Table 2) is consistent with the 450-µm map of Smail et al. (1999).

3.3 Far-infrared data

To place limits on the emission from both central galaxies at wavelengths between 12 and 100 µm, we used the xscantel facility at the Infrared Processing & Analysis Center to analyse co-added survey data from the IRAS. We found a 60-µm source spatially coincident with the central galaxy of A 1835. For A 2390, there were no formal detections, but there is tentative evidence (≥ 2σ) of emission at 60 and 100 µm. For completeness, we also list in Table 2 the 7- and 15-µm flux densities for A 2390 from the Infrared Space Observatory (ISO) observations reported by Lémonon et al. (1998).

3.4 Optical and near-IR data

Smail et al. (1998b) recently published a photometric survey of ten moderate-redshift, X-ray-luminous clusters. They found that four of the central cluster galaxies had very blue ultraviolet–optical colours; bluer than the bulk of their red, spheroidal cluster members, and bluer than the central galaxies in the remaining clusters. The most extreme examples were the central galaxies in the two clusters discussed here, A 1835 and A 2390. At rest-frame wavelengths of ∼ 3500 Å, they have luminosities a factor of two in excess of those expected from their rest-frame optical fluxes assuming a normal giant elliptical SED. We list the ultraviolet and optical photometry for both cluster galaxies in Table 2.

The $UBI$ photometry from Smail et al. (1998b) includes total $I$-band magnitudes and seeing-matched aperture photometry in $UBI$ within 3.0-arcsec-diameter apertures. These measurements have been corrected for reddening assuming $E(B - V) = 0.14$ towards A 2390 and $E(B - V) = 0.05$ towards A 1835. Photometric errors include an estimated uncertainty in the reddening corrections of 10 per cent.

Near-infrared photometry for the central galaxies of A 2390 and A 1835 is listed in Table 2. These data were obtained at the 3.8-m UK Infrared Telescope (UKIRT) using IRCAM3, a 256$^2$ InSb array, on the nights of 1998 July 11–16. The conditions were photometric and the seeing varied from 0.8 to 1.2′′. For photometric calibration, we employed UKIRT faint standards (Casali & Hawarden 1992).

In addition to the ground-based images described earlier, we have also made use of archival $HST$ WFPC2 images of A 2390 (Pelló et al. 1999). These data comprise a 8.4-ks integration in F555W ($V$) and a 10.8-ks integration in F814W ($I$) and provide deep imaging of the central cluster galaxy at an effective resolution of ∼ 0.5 kpc (Fig. 1). Evidence for both dust and the presence of a powerful nuclear source can be found in these images (c.f. Lémonon et al. 1998). A distinct bi-conical structure bisected by a strong dust lane around 0.5 arcsec, or 1 kpc, in length is shown in Fig. 1. The cones are significantly bluer than the galaxy as a whole and have an opening angle of 20–30°. These cones are similar to those seen in Seyfert galaxies where they result from direct ionization by the nuclear source. Although the radio emission is relatively amorphous, on the smallest scales discernable from the VLA data there is weak evidence for a component oriented orthogonally to the optical cones.

Figure 1. The archival $HST$ WFPC2 images of the central galaxy in A 2390. We show the F555W exposure on the right and the F814W on the left. There are obvious differences between the morphological appearance of the galaxy in the two bands. To emphasise these differences, we have scaled and subtracted the F814W image from the F555W exposure to remove the contribution from the red stellar halo of the galaxy. We show this colour-subtracted image in the central panel, which shows the blue jet (black) and a red dust lane crossing it (white). The panels are each 10 × 10 arcsec square (47 kpc at the cluster redshift) and North is 19.3° counter-clockwise from the vertical axis. The thin white lines roughly delimit the boundaries of the blue emission cone seen in the (F555W–F814W) image.
seen in the HST images (c.f. A 1795, McNamara et al. 1996, where these components are aligned).

4 ANALYSIS AND RESULTS

We now employ the observations outlined in §3 to investigate the nature of the sub-mm emission detected in the central galaxies of A 1835 and A 2390.

4.1 A 1835

The SED of the central galaxy of A 1835 from radio wavelengths to the ultraviolet is shown in Fig. 2. To determine the possible non-thermal contribution to the emission at sub-mm wavelengths we extrapolate the synchrotron radio emission from 1.4–28 GHz (with $\alpha = -0.8$, where $F_\nu \propto \nu^\alpha$) into the sub-mm waveband. This extrapolation falls more than an order of magnitude short of the flux density detected at 850 $\mu$m and several orders of magnitude below that at 450 $\mu$m. The detection of modest emission at 60 $\mu$m (§3.3) is three orders of magnitude in excess of the extrapolated radio continuum. This suggests that most of the sub-mm emission from the central galaxy in A 1835 is due to thermal emission from dust and represents the first unambiguous evidence for dust in emission in the central regions of a cooling-flow cluster.

The far-IR and sub-mm data are fit adequately by the luminous IRAS galaxy template SED compiled by Guiderdoni et al. (1998), which demonstrates that warm dust heated by hot stars in a starburst is a plausible emission mechanism, though we can not rule out some contribution to the dust heating, possibly even a dominant contribution, from the galaxy’s active nucleus (see, for example, Ivison et al. 1998, 1999).

The mass of dust estimated from these observations is extremely sensitive to its assumed properties, particularly the temperature, $T_d$. We are helped here by the 60-$\mu$m detection of A 1835, which allows us to constrain $T_d$ to 40 ± 5 K if the dust remains optically thin throughout the far-IR and obeys an emissivity law with index +1. Even if the dust becomes optically thick at 100 $\mu$m, $T_d$ cannot rise above 50 K. This temperature is significantly above the value of ~10 K expected for the cold gas condensing out of the cooling flow (Fabian, Johnstone & Daines 1994), though we cannot rule out a substantial cold dust mass (with smaller masses of dust at higher temperatures dominating the observed far-IR/sub-mm emission). An upper limit to the cold dust component could be set by the extinction of background objects behind the cluster. In particular multiply-imaged gravitational arcs provide the opportunity to compare the colours of several images of the same background object at different positions within the cluster core.

For $T_d = 40$ K, we derive a dust mass, using standard assumptions about dust properties, of $1.1 \times 10^5 M_\odot$. This falls to $0.8 \times 10^5 M_\odot$ if we allow $T_d$ to rise to 50 K.
We show the composite non-thermal and dust spectrum fit to our observations in Fig. 2. Integrating the flux between 10 μm and 2 cm from the dust component we derive an integrated flux of $1.3 \times 10^{-14}$ W m$^{-2}$. This translates into a far-IR luminosity of $L_{\text{FIR}} \sim 10^{12} L_\odot$, placing the central galaxy in A 1835 on the boundary of the class of ultra-luminous IR galaxies (ULIRGs) defined in Saunders & Mirabel (1996).

Assuming that all of this far-IR emission is powered by star formation, we can convert the $L_{\text{FIR}}$ into a star-formation rate (SFR). Depending upon the exact conversion recipe chosen this yields SFRs of 140–240 $M_\odot$ yr$^{-1}$ (Leitherer & Heckman 1995) or 200–600 $M_\odot$ yr$^{-1}$ (Thronson & Telesco 1986). The estimate of 200–400 $M_\odot$ yr$^{-1}$ based upon the Hα luminosity and young stellar content of this galaxy (Allen 1995) compares favourably with these values, considering the differences in the assumed IMF. Clearly, if the far-IR luminosity is supplied by stars then this galaxy is undergoing a substantial episode of star formation.

4.2 A 2390

The SED of the central galaxy in A 2390 (Fig. 3) is quite different from that of A 1835, with a radio flux almost an order of magnitude stronger - the radio source in A 2390 is powerful compared to other central cluster galaxies in Abell clusters (Ledlow & Owen 1995). Moreover, the radio spectrum shows signs of self-absorption effects with a turnover at around 1–3 GHz, indicating that the radio source is probably very compact.

Turning to the mm/sub-mm detections, we see that these fall close to an extrapolation of the radio spectrum arising from the non-thermal nuclear source. If the flux densities at 1350 and 2000 μm are due entirely to non-thermal processes, then the spectral index from those points and the 15-, 22- and 43-GHz radio points is $\alpha = -0.88 \pm 0.08$.

The extrapolation of this power law to 850 μm yields 6.5 ± 1.0 mJy, and so the observed flux at 850 μm then indicates a marginally significant excess of 3.4 ± 1.6 mJy. This is comparable with the dust emission in A 1835 and hence the dust mass and SFRs inferred would also be similar.

An alternative extrapolation of the non-thermal emission would be a power law of the form $\alpha = -0.73 \pm 0.03$, which can account for all the observed data points from 7 μm to 5 cm, and only over-predicts the 1350- and 2000-μm fluxes at the 2- and 1-σ levels, respectively. This second model of the non-thermal emission would leave no room for a substantial contribution from dust emission at 850 μm. This conclusion is not significantly affected by relative calibration errors between the radio and sub-mm as the observed excess is found within sub-mm band alone where the same planetary calibrator is used.

Without a robust detection of emission at shorter wavelengths (e.g. 450 μm) we cannot differentiate between the two possible models of the non-thermal contribution to the sub-mm emission and prove whether we see dust emission from this galaxy. However, the tentative IRAS detections at 60 and 100 μm do support the presence of some warm dust and the HST images clearly show that some dust is present. Adopting an $\alpha = -0.88$ power-law and assuming that the dust properties are similar to those inferred for the central galaxy of A 1835, we would expect a dust mass of around $0.6 - 0.8 \times 10^8 M_\odot$ in A 2390.

A claim has recently been made for substantial dust emission from the central galaxy of A 2390 using mid-IR observations from ISO at 7 and 15 μm (Léonon et al. 1998, L98). We can conclude that the excess of flux at 15 μm is very probably due to dust but L98 severely underpredict
the potential non-thermal contribution due to the problems with phase calibration in the VLA data used by L98 — see §3.1. Therefore additional evidence for dust in A2390 exists but the ambiguity introduced by the non-thermal continuum and the uncertainties in dust opacity, temperature and aperture effects prevent us from drawing any quantitative conclusions from the ISO data alone.

To further clarify the nature of the sub-mm emission mechanism in A 2390 observations in the far-IR are required. Using SCUBA at 450 µm, the expected flux is around 20 mJy if dust is present, and a detection at this level is feasible in good conditions. Alternatively, a PHT observation from ISO at 90 µm exists (P.I. Cesarsky). This might optimistically reach an rms level of 10 mJy beam$^{-1}$ and so provide confirmation of our tentative 850-µm dust excess.

The case of A 2390 clearly illustrates the problems that can be encountered if only a few data points are available in an SED and at least two emission mechanisms are at play. Even with the extensive dataset presented here we can only present at best tentative evidence of dust emission in this galaxy. This is a cautionary lesson for future observers to build as broader spectrum as possible before concluding dust emission is present.

5 DISCUSSION AND CONCLUSIONS

The observation of sub-mm emission in the central galaxy of A 1835 represents the first unambiguous detection of dust emission in the core of a cooling flow. It provides an estimate of the total dust mass in the core of this very massive cooling flow of around $10^8 M_\odot$. This dust is detected within a radius of 70 kpc of the cluster centre where $\sim 10^{12} M_\odot$ of cold gas could have been deposited, if the cooling flow has existed in its present state for the last 10 Gyr (Allen et al. 1996). A minimum lifetime for the dust in this region is set by the timescale for destruction due to spluttering by X-rays, which is only 0.1–1.0 Gyr (Dwek & Arendt 1992). However, the dust may reside in a shielded environment resulting in a much longer lifetime. Nevertheless, assuming that the dust is associated with the cooling gas and that the dust will only survive for 0.1 Gyr, the corresponding gas-to-dust ratio could be around $10^3$, an order of magnitude greater than the standard Galactic value. Therefore, despite obtaining a reliable measure of the dust mass, it is not possible to set any firm limits on the total gas mass as the timescales for both the production and destruction of dust are short and the origin of the dust is unclear.

The observed dust temperature of $\sim 40$ K is significantly warmer than would be expected from cold clouds (Ferland et al. 1994), and so it is likely that the dust is warmed by, or is formed in, regions of star formation. The presence of an additional, dominant, cold dust component is possible though, and it is difficult to set an upper limit since any warm dust will inevitably dominate the observed emission (Frayer et al. 1999).

The vigorous star formation implied for A 1835 is supported by the tentative detection of Wolf-Rayet features in the optical spectrum (Allen 1995). The short lifetimes of these WR stars, coupled with the exceptional size of the cooling flow in A 1835, implies that these massive stars may be constantly replenished and that this system is a sustained starburst. The far-IR luminosity of the central galaxy in A 1835 classes it as a ULIRG, while in A 2390 the exact classification depends upon the interpretation of the non-thermal component. The properties of both these galaxies may be more useful to our understanding of dusty, strongly star-forming galaxies at earlier epochs — particularly those in high density environments — than more luminous, but isolated local ULIRGs (e.g. Arp 220). In particular, it is often argued that luminous radio sources at high redshift inhabit high-density environments (Hughes & Dunlop 1998) and may have associated cooling flows (Fabian et al. 1986). The recent SCUBA detection by Best et al. (1998) of 3C 324, a radio galaxy at $z = 1.2$ within an X-ray luminous cluster (Smail & Dickinson 1995; Crawford & Fabian 1996) illustrates this. Thus, the nature of these distant radio galaxies might be best probed through the detailed study of the star formation in galaxies such as A 1835 and A 2390.

This work illustrates the difficulty in detecting dust in central galaxies of cooling flows. Specifically, we have highlighted both the pitfalls of interpreting observations of central galaxies which contain strong radio sources and of relying on limited radio coverage. AJ93 demonstrated the problems for a number of lower redshift clusters where each of their detections was attributable to the associated radio source. Even for weak radio sources, say fainter than 50 mJy at 1.4 GHz, at least one frequency above 5 GHz should be mapped before sub-mm emission can be confidently associated with dust. Fortunately, the majority of central cluster galaxies fall below this flux density limit so future studies will be able to avoid the worst of these problems.

However, our detection of relatively weak sub-mm emission from only two galaxies in a sample of seven implies that substantial effort will be required to detect other central cluster galaxies and that it is unlikely that dust emission will be detectable in typical central cluster galaxies at low redshift with current instrumentation. However, by combining detailed spectroscopy and sub-mm photometry and focusing on a well defined sample of the most massive cooling flow clusters we may achieve a clearer understanding of the physical processes responsible for star formation in cooling flow galaxies.

In the longer term with the advent of large sub-mm interferometer arrays the number of detectable central galaxies should increase dramatically. The detection of dust masses as low as $10^6 M_\odot$ will be possible in relatively short exposures, allowing the study of less extreme cooling flows. Detections at shorter wavelengths, 50–350 µm, will also provide more stringent constraints to be imposed on the mass and temperature of the dust. These wavelengths are inaccessible currently but will be easily within the capabilities of SIRTF, SOFIA and FIRST.

To conclude, the detection of dust emission in the sub-mm from the core of a cooling flow has revealed an additional and substantial baryonic component in this dense region. Future work will reveal how representative this detection is, and how it relates to the deposition of gas within cooling flows in general.

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