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Far-infrared emission of intracluster dust in the Coma galaxy cluster*

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Abstract. The ISOPHOT C200 camera aboard ISO has been used to observe the extended far infrared (FIR) emission from the Coma cluster of galaxies. Two scans with 48′ length across the cluster, each at 120 μm and 185 μm, were obtained at crossing position angles. The profiles of the surface brightness ratio $I_{120\mu\mathrm{m}}/I_{185\mu\mathrm{m}}$ along the two scans are quite similar in showing an enhanced 120 μm emission within the central region of $\approx 10'$ (0.4 Mpc) diameter. This flux excess is interpreted as thermal emission from intracluster dust with a temperature slightly higher than the galactic foreground cirrus. A conservative value for the excess surface brightness at 120 μm is ≈ 0.1 MJy/sr, corresponding to a total net flux of ≈ 0.7 Jy. Depending on the dust opacity and temperature, a total dust mass of $6.2\times10^7 M_\odot \lesssim M_\mathrm{D} \lesssim 1.6\times10^9 M_\odot$ is inferred. The detected excess emission represents the first direct evidence from FIR observation for intracluster dust in a galaxy cluster. Since dust is destroyed effectively by the hot intracluster medium, the dust detected may result from galaxy stripping during the ongoing merging process in Coma. FIR emission from intracluster dust thus might be used as a tool to search for non-equilibrium galaxy clusters.

Key words: galaxies: clusters: individual: Coma – galaxies: clusters: general – intergalactic medium – infrared: general

1. Introduction

The presence of dust distributed in the intergalactic medium of galaxy clusters is of considerable interest for studies of the large scale structure and cosmology such as the number counts of galaxies and quasars as well as the study of the evolution of galaxies and clusters of galaxies.

There has been quite some debate over this issue in the past few decades, mainly concentrated on indirect indications such as the visual extinction derived from number counts of background galaxies and quasars seen through foreground galaxy clusters. The results of these studies, however, are controversial (e.g. Ferguson 1993; Maoz 1995, and references therein) and as yet no consensus has been reached whether counts of background objects are really affected by foreground galaxy clusters. The indication for intracluster dust from these optical studies is therefore rather weak.

Since the suspected cold intracluster dust will radiate mainly in the far infrared (FIR), the IRAS database has been used to search for FIR excess emission towards galaxy clusters (Wise et al. 1993). After removal of galactic cirrus emission using a two-dimensional fitting procedure, indication for diffuse excess emission was found in several out of 56 clusters, but always at low significance level. Observations at even longer submillimeter wavelengths also did not find clear evidence for extended diffuse emission in a sample of 11 clusters (Annis & Jewitt 1993).

For the particular case of the Coma cluster of galaxies (Abell 1656, z = 0.02316, distance 138 Mpc, H_0 = 50 km s^{-1} Mpc^{-1}) Dwek et al. (1990) have made detailed calculations of the expected diffuse FIR flux from dust in the intracluster medium. In a steady-state approximation it was assumed that the dust is distributed over the whole cluster volume with several Mpc diameter. The model took into account grain destruction and grain heating by the hot intracluster medium as well as dust continuously injected into the intracluster medium by galactic winds. Using the IRAS upper limit of < 7 MJy/sr (which includes zodiacal and galactic foreground emission) for any diffuse FIR emission, Dwek et al. (1990) estimated that the dust in the intracluster medium, averaged over a volume with 6 Mpc (150′) diameter, must be significantly depleted compared to galactic values and concluded that the reported visual extinction of $\approx$ 0.3 mag for Coma (Zwicky 1962, Karachentsev & Lipovetskii 1969) could not be attributed to the presence of intracluster dust.

The diffuse FIR flux at 100 μm predicted by Dwek at al. (1990) for the core region (0.2 Mpc radius) of the Coma cluster

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is ≈ 0.2 MJy/sr. Such flux levels are expected to be detectable with the ISOPHOT experiment aboard ISO (Lemke et al. 1996). Compared to other searches for diffuse FIR emission, particularly the study of Wise et al. (1993), ISOPHOT has moreover the advantage that a much more accurate removal of foreground galactic cirrus emission can be accomplished by observing the cluster at longer wavelengths. As a pilot study of cold dust in galaxy clusters, a search for extended FIR emission in the direction of the Coma cluster of galaxies has been carried out with ISOPHOT to demonstrate the feasibility and the scientific potential of the instrument as well as to initialize further studies of other galaxy clusters. The results of this investigation are presented in this paper.

2. Observations and data reduction

The Coma cluster was observed with the C200 subexperiment of ISOPHOT during revolution 247 on July 21, 1996. The C200 is a 2×2 pixel array of stressed Ge:Ga with a pixel size of 89.″4. Two linear scans across the cluster center (α_{2000} = 12$^{\rm h}$ 59$^{\rm m}$ 35$^{\rm s}$ δ_{2000} = 27° 57$^{\rm m}$ 38$^{\rm s}$) were obtained at position angles (PA) 82° and 36°, respectively. The PAs were chosen such that the first scan covered the two central galaxies, NGC 4874 and NGC 4889, while the second crossed the diffuse luminous intergalactic material (Welch & Sastry 1971, Mattila 1977) extending southwest from the cluster center.

Each PA was observed with both the C_120 and C_180 filters (central wavelength 120 μm and 185 μm, equivalent widths 47 μm and 72 μm, respectively) covering the same sky positions. Each scan has a length of 48′, starting 24′ from and crossing the cluster center. It consists of 16 steps with 3′ positional offset from one step to the next, resulting in almost no detector overlap between successive sky positions. At each sky position, 5-6 integrations in sample-up-the ramp mode were obtained, where each ramp consists of 127 non-destructive readouts during 8 sec integration time. Including overhead, the resulting total telescope time of the observation was 1 hour. The observed sky positions are shown in Fig. 1, overlaid on a combined optical / X-ray image (Vikhlinin et al. 1997).

The acquired data sets were reduced within the ISOPHOT Interactive Analysis Software (Gabriel et al. 1997). However, the basic algorithms for ramp - deglitching (correction for cosmic ray hits during the ramp integration), ramp fitting (derivation of the signal per integration) and averaging of the signals at each sky position was replaced by a procedure which made use of the differences between consecutive non-destructive readouts belonging to the same sky position. This algorithm analyses the distribution of the pairwise readout-differences to detect and flag glitches and derives a mean signal for each sky position from the unflagged pairwise differences. Since the observation of the first sky position of each scan succeeded a measurement with the on-board calibration source, it showed noticeable detector drift in the pairwise signal differences. Therefore, an attempt for a drift-correction was made in the processing. Additionally, other estimators for the central value of the pairwise differences such as Tukeys (1977) biweighted mean and an annealing M estimator (Li 1996) were used to check the resulting signal at each sky position. Because the final results were almost identical to the method which utilizes the simple mean for the derivation of the signals, they will not be discussed further.

Observations of the ISOPHOT Fine Calibration Source (FCS) at the beginning and end of each scan in each filter were used for flux calibration and to monitor possible changes in the detector response. Each sky position of each scan in each filter was separately flux calibrated using the two accompanying FCS measurements linearly interpolated in time. The absolute flux calibration of ISOPHOT is still preliminary with an overall uncertainty of about 30 %. However, it should be stressed that the main conclusion of this paper, namely the first detection of diffuse FIR emission of intracluster dust, is completely independent of an absolute flux calibration. Derived properties of the dust, however, depend on the flux calibration and will eventually undergo small numerical corrections once the final calibration will have been established after the mission.

3. Results

The distribution of the measured surface brightness, averaged over the four C200 detector pixels, as a function of distance to the cluster center for both filters is shown for PA 82° and 36° in Fig. 2a and 2b, respectively. Despite significant structure mostly due to galactic cirrus foreground emission, the flux levels at the crossing of the two scans agree within ≈ 10 % at both wavelengths. All four distributions show a high signal at the very first sky position due to the above mentioned detector drift resulting from the preceding FCS calibration measurement.

Fig. 2a (PA 82°, labeled with the scan direction 'West-East') shows at both wavelengths a prominent source close to the end of the scan, which is identified with IC 4040 (IRAS F12582+2819, 5C 04.108), a peculiar $m_{\rm V}$ = 15 mag spiral galaxy (z = 0.02615) with a dust pattern (Andreon et al. 1996). It has a broadband spectrum which rises steeply towards the FIR with a 100 μm IRAS flux of 2.6 Jy. Since this source lies just outside the field of view, only the outer parts of the point spread function was sampled with the two northern pixels. Therefore, it is not possible to derive total fluxes at 120 μm and 185 μm for IC 4040. Remarkably, although the scan along PA 82° covered both NGC 4874 and NGC 4889 (Fig. 1), neither of the two dominant elliptical galaxies in the center of Coma were detected. In Fig. 2b (PA 36°, scan direction 'South-North'), a weak bump is discernible near -10′ (south-west) from the cluster center, which might be due to the luminous intracluster material detected on deep optical images (Welch & Sastry 1971, Mattila 1977).

Fig. 3a shows the flux ratio $I_{120\mu{\rm m}}/I_{185\mu{\rm m}}$ for the two scans separately. Again, the ratio has first been derived for each detector pixel separately and subsequently been averaged. The flux ratios for both scans have a similar appearance in showing an almost symmetric broad bump about the cluster center while at larger distances there is some scatter around an almost linearly decreasing level of the flux ratio. There is some indication that the bump is more extended along PA 82° compared to PA 36°.

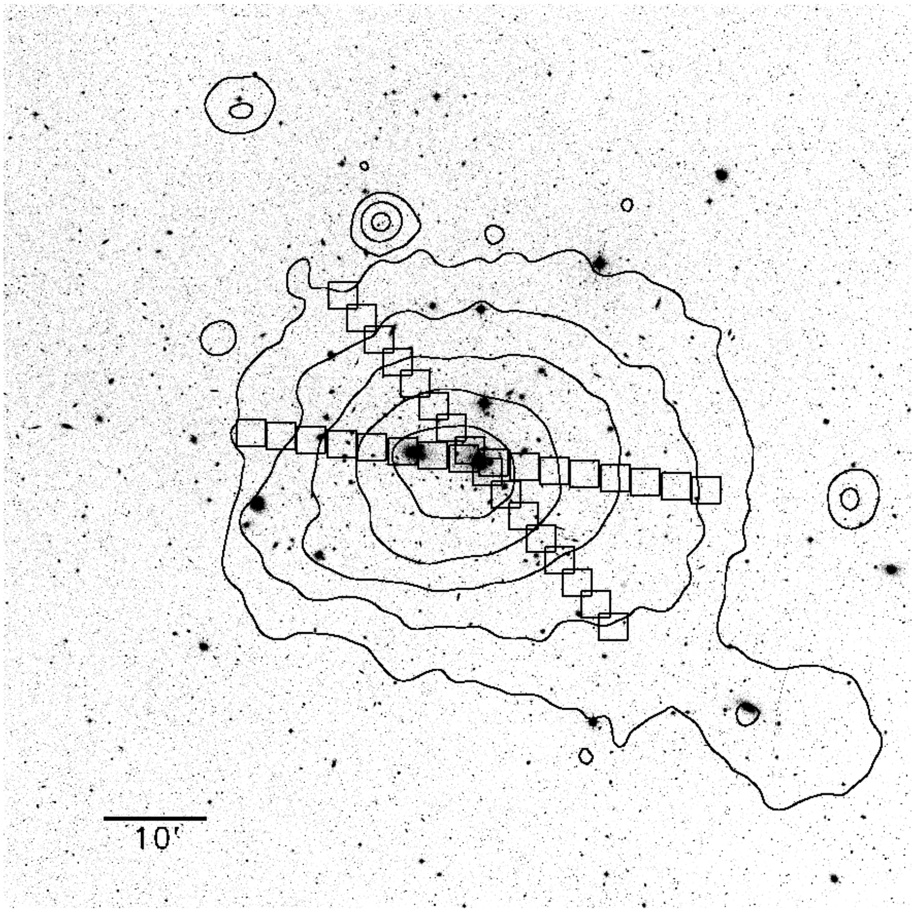

Fig. 1. The sky positions observed with ISOPHOT (squares) overlaid on the combined optical (POSS) image and X-ray (ROSAT) isophotes (Vikhlinin et al. 1997) of the Coma galaxy cluster. North is up and east to the left. The central galaxy pair is NGC 4874 (western component) and NGC 4889 (eastern component). Note the non-circular X-ray isophotes elongated roughly along the East - West direction

The mean of the flux ratio of both scans (Fig. 3b) shows the central excess quite clearly. Taking into account the scatter in the outer parts of the distribution, at least the four innermost points spanning a diameter of $\approx 10'$ lie above a somewhat slanting background. The height of the excess is roughly 3%. The outer regions in Fig. 3b indicate that the emission from galactic cirrus as well as that of cluster galaxies can be removed by a scaled subtraction of the 185 μm from the 120 μm flux distribution. Assuming that the $I_{120\mu m}/I_{185\mu m}$ flux ratio is a smooth function of position across the cluster, a straight line was fitted to the outer parts of the $I_{120\mu m}/I_{185\mu m}$ ratio (dashed line in Fig. 3b). The flux at 185 μm was subsequently scaled using this linear function of position, subtracted from the 120 μm flux and averaged over both PAs and the four detector pixels. From the difference (Fig. 4) an averaged 120 μm flux excess of ≈ 0.1 MJy/sr over the central area with $10'$ diameter was derived. This value represents a lower limit to the diffuse 120 μm emission from Coma.

4. Discussion

The almost symmetrical central bump in the foreground subtracted 120 μm flux distribution (Fig. 4) indicates the presence of extended FIR emitting material in the central region of the Coma cluster. At a distance of D = 138 Mpc the central $5'$ radius corresponds to 0.2 Mpc, the innermost shell of the calculations by Dwek et al. (1990), where a FIR emission of ≈ 0.2 MJy/sr at 100 μm has been predicted from intracluster dust heated by the hot intracluster medium. The excess emission seen in Fig. 4 is thus interpreted as being due to thermal emission of cold dust. The diffuse FIR emission represents the first direct evidence from FIR observations for dust in the intracluster medium of the Coma cluster.

The temperature predicted by Dwek et al. (1990) for the intracluster dust is ≈ 20 K, while the large scale emission of galactic dust has a temperature of ≈ 17 - 23 K (Sodrowski et al. 1994, Dwek et al. 1997). The excess seen in Fig. 3 therefore indicates that the intracluster dust is slightly warmer than the galactic dust or has different properties such as grain size, grain composition, or emissivity. An independent determination of the dust temperature is hampered by the lack of accurate fluxes for the zodiacal light and the cirrus foreground emission in the direction of Coma.

However, from the absence of a noticeable bump in the $I_{120\mu m}$ and $I_{185\mu m}$ surface brightness distributions (Fig. 2) near the cluster center, a lower limit to the dust temperature T_D can nevertheless be derived. Assuming a conservative upper limit for any diffuse extended emission at 120 μm and 185 μm of $\lesssim 0.3$ MJy/sr, the flux difference from Fig. 4 together with the linear ($I_{120\mu m}/I_{185\mu m}$) relationship for the zodiacal and cirrus foreground from Fig. 3b gives a flux ratio limit of $I_{120\mu m}/I_{185\mu m} \gtrsim$

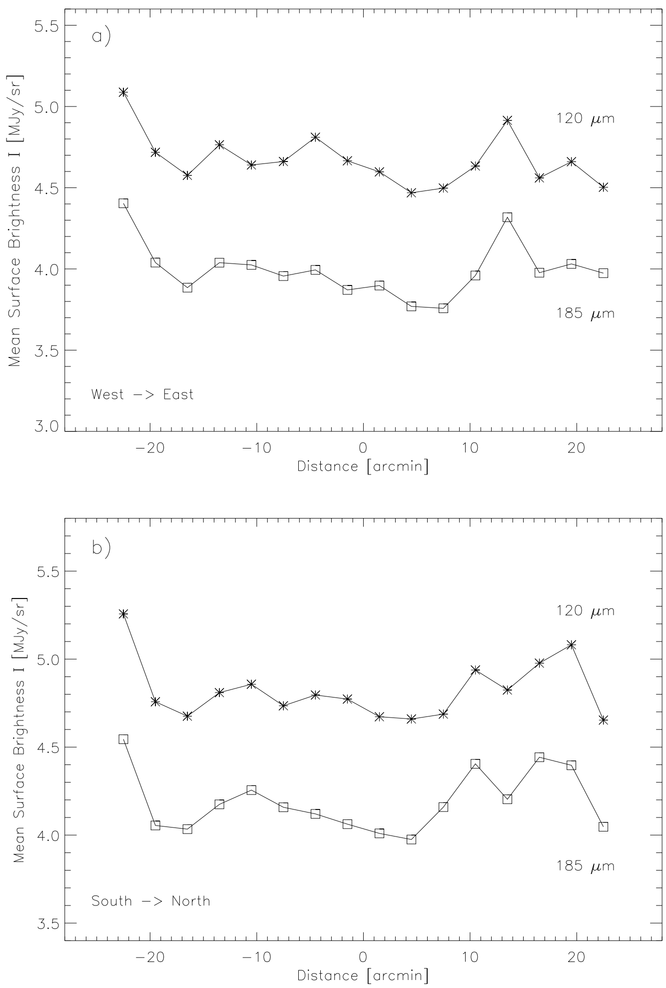

Fig. 2a and b. Surface brightness at 120 μm (asterisks) and 185 μm (squares) along position angle 82° (scan direction West-East) (**a**) and 36° (scan direction South-North) (**b**), averaged over all four C200 detector pixels, as a function of distance from the cluster center. In **a**, the source about 15′ east of the center is the galaxy IC 4040.

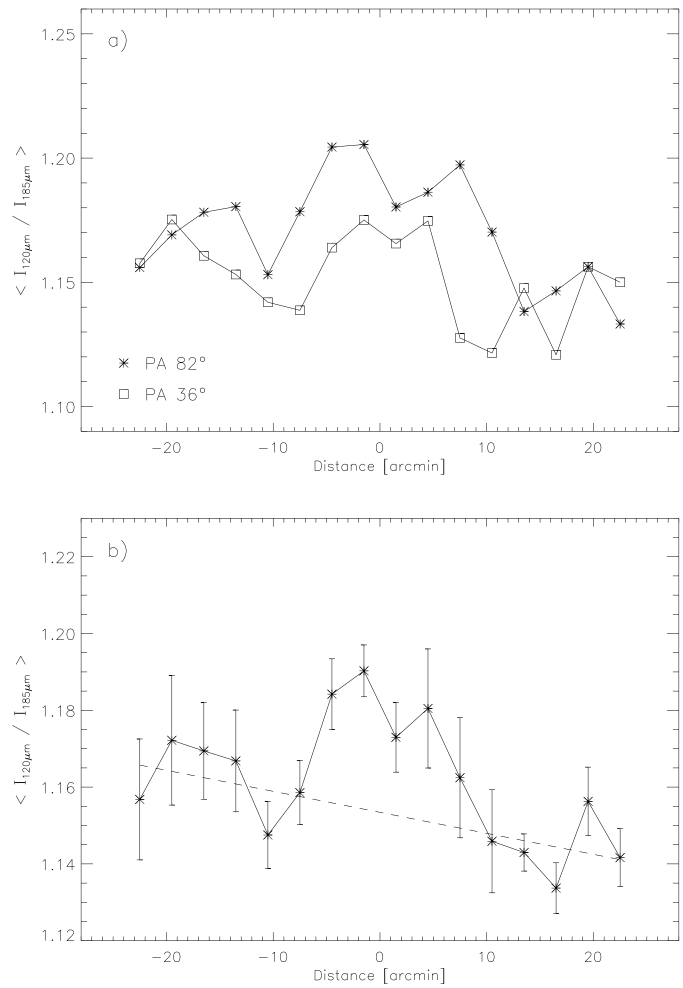

Fig. 3. a Surface brightness ratio $I_{120\mu\mathrm{m}}/I_{185\mu\mathrm{m}}$ along position angle 82° (asterisks) and 36° (squares) as a function of distance from the cluster center. Both distributions show a centrally symmetric bump indicating a cold component emitting at 120 μm. **b** Surface brightness ratio $I_{120\mu\mathrm{m}}/I_{185\mu\mathrm{m}}$ averaged over both position angles as a function of distance from the cluster center. Error bars represent the standard error of the mean of the eight averaged individual ratios at each sky position. The dashed line represents a linear fit to the outer regions (distance $\geq 10'$).

1.7. If the flux at a particular wavelength is given by a Planck function $B_\nu(T_\mathrm{D})$ modified by an emissivity index n,

$$F_\nu = \nu^\mathrm{n} B_\nu(T_\mathrm{D}), \tag{1}$$

this ratio can be reconciled with dust temperatures $T_\mathrm{D} \gtrsim 26$ K for n = 2 and $T_\mathrm{D} \gtrsim 38$ K for n = 1. It should be stressed that these limits are only exemplary since they depend very sensitively on the values used for the scaling factor (Fig. 3b) and the averaged flux difference (Fig. 4). Similarly, an upper limit for the dust temperatures can be derived if an upper limit from the IRAS 60 μm map is assumed. Taking $I_{60\mu\mathrm{m}} \lesssim 0.3$ MJy/sr and the lower limit $I_{120\mu m} \gtrsim 0.1$ MJy/sr (Fig. 4) gives $I_{60\mu\mathrm{m}}/I_{120\mu\mathrm{m}} \lesssim 3$, which can be reconciled with $T_\mathrm{D} \lesssim 55$ K for n = 2 and $T_\mathrm{D} \lesssim 80$ K for n = 1.

A conservative value for the 120 μm net surface brightness is the averaged value of ≈ 0.1 MJy/sr (Fig. 4) within the central 10′ diameter (6.6×10^{-6} sr). The total flux density is then $F_{120\mu\mathrm{m}} \approx 0.7$ Jy, corresponding to a FIR luminosity $L = 4\pi D^2 \nu F_\nu$ of $L_{120\mu\mathrm{m}} \approx 4 \times 10^{43}$ erg/sec.

The mass of the emitting dust M_D can be derived from

$$M_\mathrm{D} = D^2 F_\nu \left[\kappa_\lambda B_\nu(T_\mathrm{D})\right]^{-1} \tag{2}$$

(Hildebrand 1983, Draine 1990), where F_ν is the total flux density, D the cluster distance, and κ_λ the dust opacity. For dust opacities at 120 μm Draine (1990) gives a range 0.02 $\mathrm{m^2/kg} \lesssim \kappa_{120\mu\mathrm{m}} \lesssim 0.08\ \mathrm{m^2/kg}$. The range of a factor ≈ 4 for the dust opacity reflects the different assumptions about grain sizes and composition used for the calculations of κ_λ. The dust opacity κ_λ therefore represents the major uncertainty in deriving dust masses from observed FIR fluxes (Draine 1990). Using these dust opacities and a temperature range 25 K $\leq T_\mathrm{D} \leq 40$

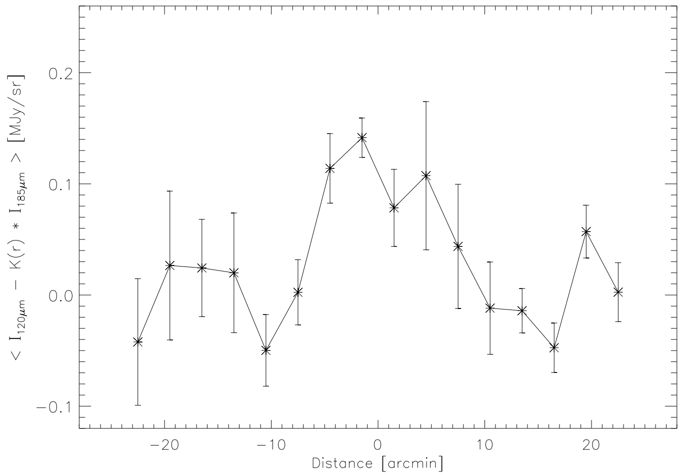

Fig. 4. Net 120 μm surface brightness after a scaled subtraction of the observed 185 μm surface brightness using the linear relation from Fig. 3b. Error bars represent the standard error of the mean of the eight individual differences at each sky position. The remaining 120 μm net surface brightness averaged over the central 10′ diameter is ≈ 0.1 MJy/sr.

K, a total dust mass of $6.2 \times 10^7 M_\odot \lesssim M_{\rm D} \lesssim 1.6 \times 10^9 M_\odot$ within the central volume with 0.2 Mpc radius is derived. This is roughly a factor 10 higher than the dust content of dominant central galaxies in clusters with strong X-ray emission (Bregman et al. 1990).

The mass of intracluster gas within 0.3 Mpc derived from ROSAT PSPC X-ray images is $M_{\rm gas} \approx 1.6 \times 10^{13} M_\odot$ (Buote & Canizares 1996). Since the core radius of the X-ray emitting gas is about the same size (Burns et al. 1994), the gas mass within 0.2 Mpc, the region where FIR emission has been detected, can be rescaled assuming a constant gas density, which gives $M_{\rm gas} \approx 5 \times 10^{12} M_\odot$. The average dust-to-gas ratio is then $1.3 \times 10^{-5} \lesssim M_{\rm dust}/M_{\rm gas} \lesssim 3.2 \times 10^{-4}$, which indicates a dust depletion by a factor of $\approx$ 20 - 600 compared to the galactic interstellar medium (0.0075, Mathis et al. 1977).

The claimed visual extinction in Coma can be compared with the expected optical extinction associated with the intracluster dust by assuming that the central region within R = 0.2 Mpc of the cluster center is uniformly filled with spherical grains of radius r and mass density ρ. The average extinction may then approximated by

$$A_{\rm V} = 1.086 \pi r^2 R M_{\rm D} Q_{\rm ext} [(4\pi/3)^2 r^3 R^3 \rho]^{-1} \quad (3)$$

(Whittek 1992), where $Q_{\rm ext}$ is the extinction efficiency factor. Taking r = 0.1 μm and ρ = 1 g cm^{-3} characteristic for silicate grains as well as $Q_{\rm ext}$ = 2, this gives 0.01 mag $\lesssim A_{\rm V} \lesssim$ 0.2 mag. Thus, only the upper end of the derived dust mass range would give rise to an observable optical extinction, but confined to the innermost region of the cluster

Since the survival time of dust grains in the hot intracluster medium is only of the order of a few 10^8 years (Dwek et al. 1990), two fundamentally different origins for a mass $6.2 \times 10^7 M_\odot \lesssim M_{\rm D} \lesssim 1.6 \times 10^9 M_\odot$ of intracluster dust appear viable: Either the dust is ejected continuously from Coma cluster galaxies as galactic winds, which will lead to a steady state between dust destruction and replenishment, or it has been stripped from an infalling galaxy group during a recent merger event. The former possibility has been assumed in the study of Dwek et al. (1990). However, the latter possibility is becoming increasingly interesting since recent optical (Colless & Dunn 1996) and X-ray observations (Vikhlinin et al. 1997; Burns et al. 1994) indicate quite convincingly that the Coma cluster is a dynamically young system in the process of merging with other galaxy groups rather than an old system having reached its equilibrium state. Particularly, Colless & Dunn (1996) have argued that a galaxy group dominated by NGC 4889 has been fallen into and already partially disrupted by merging with the Coma cluster, the central galaxy of which is NGC 4874, both of which might have been ejected from their respective parent groups, thereby possibly loosing their extended halos.

The excess emission along the PA 82° (roughly West-East) appears to be more extended than the other along PA 36° (Fig. 3a). This is in accordance with the asymmetric distribution of the X-ray emitting hot intracluster medium (Vikhlinin et al. 1997, see also Fig. 1; Burns et al. 1994) and the galaxy surface density distribution (Colless & Dunn 1996). The deviation from a symmetric dust distribution is consistent with the picture that the FIR emitting material has its origin in the recent merging process. However, this might also be expected in the steady state model of Dwek et al. (1990) if the dust distribution follows the galaxy distribution. Further evidence for the merging process as the dust origin might be the derived intracluster dust mass, which is roughly only an order of magnitude higher than the dust content of dominant cluster galaxies.

5. Concluding remarks

The detection of a FIR excess emission from the central part of the Coma cluster represents the first direct evidence for thermal dust distributed in the hot X-ray emitting plasma. Since recent observations have shown that the Coma cluster is an archetypical young cluster with ongoing merging processes, additional galaxy clusters with evidence for recent merging activity as well as with a dynamically old and relaxed appearance should be searched for FIR excess emission. If the detection of diffuse FIR emission will be restricted to clusters with undergoing or recent merger activity it would then represent an indicator for dynamically young clusters completely independent of X-ray or optical observations. This might particularly be of great importance for medium and high-redshift clusters and their formation.

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