ISO's Contribution to the Study of Clusters of Galaxies *

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Abstract. Starting with nearby galaxy clusters like Virgo and Coma, and continuing out to the furthest galaxy clusters for which ISO results have yet been published ($z = 0.56$), we discuss the development of knowledge of the infrared and associated physical properties of galaxy clusters from early IRAS observations, through the "ISO-era" to the present, in order to explore the status of ISO's contribution to this field. Relevant IRAS and ISO programmes are reviewed, addressing both the cluster galaxies and the still-very-limited evidence for an infrared-emitting intra-cluster medium.

ISO made important advances in knowledge of both nearby and distant galaxy clusters, such as the discovery of a major cold dust component in Virgo and Coma cluster galaxies, the elaboration of the correlation between dust emission and Hubble-type, and the detection of numerous Luminous Infrared Galaxies (LIRGs) in several distant clusters. These and consequent achievements are underlined and described.

We recall that, due to observing time constraints, ISO's coverage of higher-redshift galaxy clusters to the depths required to detect and study statistically significant samples of cluster galaxies over a range of morphological types could not be comprehensive and systematic, and such systematic coverage of distant clusters will be an important achievement of the Spitzer Observatory.

Received: 10 November 2004

1. Introduction

1.1. ISO LOOKS DEEP

The most strongly star forming galaxies are heavily dust obscured, and estimates of their star formation rates (SFR) made at visual wavelengths often fall one or two orders of magnitude below their true values. Frequently, very actively star forming galaxies occur in associations or groups. At the same time it has been believed that in the dense environments of galaxy clusters the interactions of galaxies with each

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[*] Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

Space Science Review ISO Special Issue.

other, with the cluster tidal field, and with the intra-cluster medium (via ram pressure) strip galaxies of their reserves of gas, and eventually suppress star formation.

Much has already been learned about the evolution of the cosmic star formation rate in field galaxies from observations with the European Space Agency's Infrared Space Observatory (ISO) satellite (Kessler et al. 1996). Thanks to deep surveys in the mid-infrared (MIR) and far-infrared (FIR) (e.g. Elbaz et al. 1999, 2002; Serjeant et al. 2000, 2004; Gruppioni et al. 2002; Lari et al. 2001; Metcalfe et al. 2003; Sato et al. 2003; Kawara et al. 2004; Rowan-Robinson et al. 2004; Rodighiero et al. 2003 and several others) conducted, respectively, with ISOCAM[1] (Cesarsky et al. 1996) and ISOPHOT (Lemke et al. 1996), we now know that the comoving density of IR-bright galaxies has a very rapid evolution from $z \sim 0$ to $z \sim 1$. This evolution has been interpreted as the result of an increased rate of galaxy-galaxy interactions, coupled with an increase in the gas content of the galaxies (Franceschini et al. 2001). Dust obscuration plays an important role in concealing star formation in field galaxies. Its role in relation to the star formation activity of cluster galaxies is less known. Published ISO results to–date addressing the fields of galaxy clusters (Duc et al. 2002, 2004; Coia et al. 2004a & b; Biviano et al. 2004; Metcalfe et al. 2003; Fadda et al. 2000; Altieri et al. 1999; Soucail et al. 1999; Barvainis et al. 1999; Quillen et al. 1999; Lémonon et al. 1998; Pierre et al. 1996.) concern a dozen clusters at $z < 0.6$, and point to an important role for dust, evolving with redshift, also in cluster galaxies. The fraction of IR-bright, star-forming cluster galaxies changes significantly from cluster to cluster, without a straightforward correlation with either the redshift, or the main cluster properties (such as the cluster mass and luminosity).

The presence of dust in cluster galaxies may have hampered our efforts to fully understand the evolution of galaxies in clusters. Optical-band observations have provided a few, but very fundamental results, which cannot yet however be combined in a unique, well constrained scenario of cluster galaxy evolution.

1.2. Some properties of cluster galaxies

Perhaps the most fundamental phenomenology that all scenarios of cluster galaxy evolution (e.g. Dressler 2004) must explain is the so called morphology density relation (hereafter MDR; Dressler 1980), whereby early-type galaxies, i.e. ellipticals and S0s, dominate rich clus-

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[1] Throughout this paper the ISOCAM filters having reference wavelengths 6.75 and 14.3 μm will respectively be referred to as the 7 μm and 15 μm filters. Both bandpasses are referred to as mid-infrared (MIR).

ters, while late-type galaxies, i.e. spirals and irregulars, are more common in the field. The fact that early-type galaxies seem to reside in the cluster centres since $z \geq 1$–2, while the colour-magnitude relation (CMR, Visvanathan & Sandage 1977) remains very tight even at $z \sim 1$ suggests that the MDR is established at the formation of galaxy clusters and that the early-type galaxies defining the CMR are uniformly old and passively evolving since their formation redshift, $z_f > 2$ (e.g. Ellis et al. 1997). Similar conclusions are obtained by analysing the fundamental plane (FP; Dressler et al. 1987), relating basic properties of early-type galaxies (their effective radius, internal velocity dispersion, and effective surface brightness). The FP, like the CMR, still holds for early-type galaxies in $z \sim 1$ clusters, and its scatter is similar to that seen in nearby clusters (van Dokkum & Stanford 2003).

However, these conclusions could only be true *on average.* Independent analyses suggest that at least part of the cluster galaxies have undergone significant evolution over the last 3–8 Gyr. First and foremost is the observational evidence for an increasing fraction of blue cluster galaxies with redshift, the so called 'Butcher-Oemler' (BO) effect (Butcher & Oemler 1978, 1984; Margoniner et al. 2001). Approximately 80% of galaxies in the cores of nearby clusters are ellipticals or S0s, i.e. red galaxies (Dressler 1980), but the fraction of blue galaxies increases with redshift. These blue galaxies are typically disk systems with ongoing star formation (Lavery & Henry 1988), with spectra characterized by strong Balmer lines in absorption (typically, EW(Hδ) $>$ 3 Å) and no emission lines, and have been named 'E+A' (or also 'k+a') galaxies (Dressler & Gunn 1983). Modelling of their spectra indicates that star formation stopped typically between 0.05 and 1.5 Gyr before the epoch of observation, in some cases after a starburst event (Poggianti et al. 1999, 2001).

Similarly, the fraction of spirals increases with redshift (Dressler et al. 1997; Fasano et al. 2000; van Dokkum et al. 2001), at the expense of the fraction of S0's. Maybe, the colour and the morphological evolution of the cluster galaxy population are two aspects of the same phenomenon. Field spirals are being accreted by clusters (Tully & Shaya 1984; Biviano & Katgert 2004), and the accretion rate was higher in the past (Ellingson et al 2001). It is therefore tempting to identify the blue galaxies responsible for the BO-effect in distant clusters with the recently accreted field spirals.

Possibly, these evolutionary trends could be reconciled with the passive evolution inferred from the CMR and FP studies by taking into account the so-called 'progenitor bias' (van Dokkum et al. 2000), namely the fact that only the most evolved among cluster early-type galaxies are indeed selected in studies of the colour-magnitude and fundamental plane relations.

1.3. A hostile environment

There is no shortage of plausible physical mechanisms that could drive the evolution of a galaxy in a hostile cluster environment. Among these, the most popular today are ram pressure, collisions, and starvation from tidal stripping (Dressler 2004), all in principle capable of depleting a spiral of its gas reservoir, thereby making it redder and more similar to a local S0.

Ram pressure from the dense intra-cluster medium can sweep cold gas out of the galaxy stellar disk (Gunn & Gott 1972) and induce star formation via compression of the gas that remains bound to the galaxy. Collisions or close encounters between galaxies generate tidal forces that tend to funnel gas towards the galaxy centre (Barnes & Hernquist 1991) eventually fueling a starburst that ejects gas from the galaxy. The cumulative effect of many minor collisions (named ‘harassment’, Moore et al. 1996), can lead to the total disruption of low surface brightness galaxies (Martin 1999). The collision of a group with a cluster can also trigger starbursts in cluster galaxies, as a consequence of the rapidly varying tidal field (Bekki 2001). Finally, the so called ‘starvation’ mechanism (Larson et al. 1980) affects a galaxy’s properties by simply cutting off its gaseous halo reservoir. This can occur because of tidal stripping, a mechanism effective in galaxy-galaxy encounters, but also when galaxies pass through the deep gravitational potential well of their cluster.

The common outcome of all these processes is galaxy gas depletion, ultimately leading to a decrease of the star formation activity for lack of fuel, and, hence, to a reddening of the galaxy stellar population. However, some of these processes induce a starburst phase before the gas depletion, and some do not.

To date, it remains unclear which physical process dominates in the cluster environment. Useful constraints can be obtained by finding *where* the properties of cluster galaxies change with respect to the field, since the different processes become effective at different galaxy or gas densities. Recently it has been found (Kodama et al. 2001; Gómez et al. 2003; Lewis et al. 2002) that a major change in the star-formation properties of cluster galaxies occurs in the outskirts of clusters (at ~ 1.5 cluster virial radii). These results would seem to exclude ram-pressure stripping as a major factor in cluster galaxy evolution, since the density of the intra-cluster medium is too low in the cluster outskirts.

Recent observations of high-z clusters seem to have complicated, rather than simplified, the issue of cluster galaxy evolution. A surprisingly high fraction of *red* merger systems has been found in these distant clusters (van Dokkum et al. 2001). The red colours of these merging galaxies and the lack of emission lines in their spectra suggest that their stellar populations were formed well before the merger events, but the occurrence of relatively recent starburst events in these galaxies is instead suggested by detailed analyses of their spectra (Rosati 2004).

1.4. An uncluttered view

A better understanding of the evolutionary processes affecting cluster galaxies can come from observations in the infrared. Dust, if present, is capable of obscuring most of a galaxy's stellar radiation, making the observed galaxy red and dim at optical wavelengths, and affecting optical estimates of the galaxy star formation activity. The effects of dust can be particularly severe if the galaxy is undergoing a starburst (Silva et al. 1998), so that we might be missing a substantial part of the evolutionary history of cluster galaxies by observing them at optical wavelengths. Since the dust-reprocessed stellar radiation is re-emitted at IR wavelengths, the IR luminosity is a much more reliable indicator of a galaxy's star formation activity (Elbaz et al. 2002).

The plan of this review is as follows: in Section 2 the development of knowledge of the infrared properties of galaxy clusters from early IRAS observations, through the "ISO-era" to the present is described. Section 2.1 considers the accumulation of data on the Virgo cluster, while Section 2.2 addresses other nearby clusters, e.g. the Fornax, Hydra, Coma and Hercules clusters. Section 2.3 discusses the significant progress that has been possible with ISO in the study of cluster galaxy properties out to moderate redshifts (< 0.6) and attempts to draw some comparison among the still rather heterogeneous sample of cluster observations. Section 2.4 reviews the status of attempts to directly observe diffuse intra-cluster dust in the infrared. Finally Section 3 summarises the current status of the field and remarks on the important opportunity represented by the Spitzer Observatory to decisively extend the field.

2. Cluster galaxies in the infrared

2.1. The Virgo galaxy cluster

Being the most nearby relatively massive galaxy cluster, the Virgo cluster has been studied extensively at all wavelengths. Already in 1983, Scoville et al. obtained 10 μm data with IRTF for 53 Virgo spiral galaxies and concluded that star formation is occurring in the nuclei of virtually all spiral galaxies independent of spectral type, with an average star formation rate (SFR) of $0.1\,\mathrm{M}_{\odot}$/yr. No correlation was found between 10 μm emission and gross properties (barred or normal, early or late spiral morphology, total optical luminosity), nor with location in the cluster. Using far- to Mnid-infrared flux correlations, they inferred a far-infrared (FIR) luminosity $\sim 2 \times 10^{10}\,L_{\odot}$ for the brightest 10 μm source in the Virgo cluster, NGC4388.

Leggett et al. (1987) made optical identifications of 145 IRAS galaxies in the 113 sguare degree field centred on the Virgo cluster and concluded that they were mostly seeing the spirals, and that the infrared properties of the Virgo cluster galaxies are indistinguishable from those of field galaxies at similar redshift. Virgo spirals were indistinguishable from field disc galaxies with normal SFRs. The typical infrared luminosity for the sample was $L_{IR} \sim 10^{9} L_{\odot}$, and the most luminous confirmed cluster sources were found to have L_{IR} = a few $\times\, 10^{10} L_{\odot}$. They concluded that the cluster environment has no effect on galaxy IR properties, even for very HI deficient galaxies. Their conclusion was however criticized by Doyon & Joseph (1989) who, using a sample of 102 Virgo spirals detected at 60 and 100 μm, were able to show that HI-deficient galaxies have lower IR fluxes, lower star formation activity, and cooler IR colour temperatures than those with normal HI content.

If cluster environment affects the interstellar medium (ISM) of cluster galaxies, one might expect the FIR, radio and FIR-radio correlation to be affected. Niklas et al. (1995) looked at the FIR-radio correlation in Virgo galaxies and suggested that, in this respect, most of the Virgo galaxies behave like normal field galaxies. Only a few early type spirals with strong central sources as well as very disturbed galaxies show a high radio excess. These are in the inner part of the cluster, where galaxies have disturbed HI-distributions, and truncated HI-disks, as shown by 21 cm observations (Cayatte et al. 1990). Measurements of molecular gas emission in radio continuum (Kenney & Young 1986, 1989) show a much less pronounced stripping effect.

In the ISO era, Tuffs et al. (2002) and Popescu et al. (2002a, b) used ISOPHOT at 60, 100 and 170 μm, to study a luminosity- and volumelimited sample of 63 S0a or later-type galaxies in the core and periphery of the Virgo cluster. They reached sensitivities 10 times better than IRAS in the two shorter-wavelength bandpasses, and the confusion limit at 170 μm. These programmes sought to extend knowledge of FIR SEDs to lower limits covering a complete sample of normal[2] late-type galaxies over a range of morphological type and star formation activity.

A significant cold dust component (with a temperature of around 18 K) was found in all morphological classes of late-type galaxies, from early giant spirals to irregular galaxies and Blue Compact Dwarfs (BCDs), and which could not have been recognized by IRAS. These results required a revision of the masses and temperatures of dust in galaxies. On average, dust masses are raised by factors of 6 to 13 with respect to IRAS results. The FIR/radio correlation is confirmed for the warm FIR dust, and is found for the cold dust. The predominance of the very cold dust component (down to less than 10 K) in BCDs was remarkable, with a few 10s of percent of the UV/Optical component appearing in the cold dust emission. The cold emission might be due to collisional dust heating in dust swept up in the intergalactic medium (proto-galactic cloud) by a galactic wind from the BCD or, alternatively, to photon heating of the dust particles in an optically thick disk, indicative of a massive gas/dust accretion phase that makes BCDs sporadically bright optical/UV sources when viewed out of the disk equatorial plane.

On average, 30% of the stellar light of spirals in Virgo is re-radiated by dust, with a strong dependence on morphological type, ranging from 15% for early spirals to 50% for some late spirals, and even more for some BCDs (Popescu & Tuffs 2002). Fig. 1, taken from Popescu & Tuffs (2002), shows the dependency of the dust contribution on the Hubble type in the Virgo cluster, and it illustrates a sequence of increasing FIR-to-total bolometric output running from normal to gas-rich-dwarf galaxies.

Leech et al. (1999) studied a sample of 19 Virgo cluster spiral galaxies with ISO's Long Wavelength Spectrometer (LWS) (Clegg et al. 1996) obtaining spectra around the [CII] 157.7 μm fine-structure line for 14 of them. [CII] line radiation provides the most important gas cooling mechanism in normal, i.e. non-starburst, late-type galaxies, balancing photoelectric heating from grains. In field galaxies [CII] is typically 10^{-3} to 10^{-2} of total galaxy FIR. The sample, drawn from both the cluster core and the cluster periphery (and being a sub-sample of the

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[2] A 'Normal' galaxy is understood to mean a galaxy not dominated by an active nucleus, with SFR sustainable for a substantial fraction of a Hubble time.

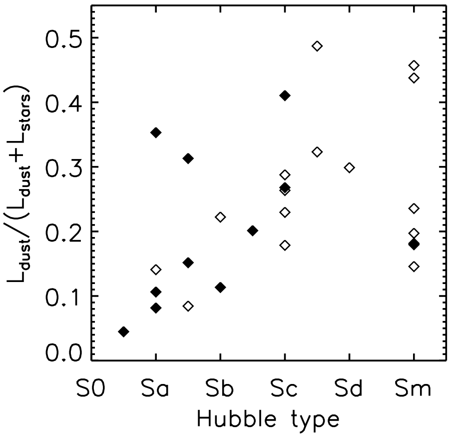

Figure 1. From Popescu & Tuffs (2002): The ratio of dust luminosity to total bolometric luminosity as a function of Hubble Type, for Virgo cluster galaxies. Filled symbols are cluster core galaxies and open symbols refer to the cluster periphery. A correlation is established between Hubble type and the FIR contribution to bolometric luminosity.

Tuffs et al. 2002 sample), spanned the S0a–Sc morphological range to probe any difference in the [CII] emission between different types or between core and periphery galaxies.

A good correlation was found between the strength of the [CII] line and the FIR flux, as measured by IRAS. Moreover, the [CII]-to-K'-band flux ratio shows a two order of magnitude difference between early-type galaxies and late spiral types. Galaxies with large [CII]/FIR ratios tend to have later Hubble types. No apparent relationship was found between [CII] strength and galaxy position in the cluster, nor between [CII] and HI-mass surface density. Any influence of the Virgo cluster environment on the [CII] emission was found to be small compared with the strong dependence of the line emission on basic measurables such as morphology or bulk mass of the stellar component, as measured by the near-IR (K'-band) luminosity.

In a series of papers, Boselli et al. (1997a,b, 1998, 2003a,b, 2004) explored the properties of a large sample of ISO-detected spiral and irregular galaxies in the Virgo cluster, in measurements made with ISOCAM at 7 and 15 μm. 71 objects were in the cluster periphery (≥ 4 degrees from M87) and 28 in the core (≤ 2 degrees from M87) in order to allow study of the effects of the environment on dust emission and evolution. A further 24 Virgo cluster galaxies were serendipitously observed, bringing the full Virgo sample up to 123 galaxies. S0 and elliptical galaxies observed by chance in the ISO fields were used to establish the stellar contribution to the IR emission. Objects had luminosities in the range $10^{7.4} \leq L_{FIR} \leq 10^{10.1}\, L_{\odot}$.

Thirty four of the Virgo objects were fully resolved by ISOCAM, and MIR images could be presented for these, along with radial light and colour profiles and other morphological and structural information.

Boselli et al. showed that the MIR emission of optically-selected, normal early-type galaxies is dominated by the Rayleigh-Jeans tail of the cold stellar component, while that of late-type galaxies is dominated by the thermal emission from dust, but partly contaminated by stellar emission, especially at $7\,\mu$m in early-type spirals (Sa). While the MIR emission (per unit mass) of the spirals and later systems are comparable, the average $7\,\mu$m and $15\,\mu$m to K' flux ratio of E, S0 and S0/a galaxies is significantly lower than that of spirals. At $15\,\mu$m, where the difference is clearer, spirals have on average a MIR emission per unit mass higher by more than one order of magnitude than E-S0/a. BCDs have, on average, a MIR emission per unit mass comparable to that of spirals.

The IR emission carriers and their behaviour are consistent with quantitative expectations based on MIR studies of the ISM in our Galaxy. In spiral and irregular galaxies the $7\,\mu$m emission is almost entirely due to the UIB[3] carriers. The MIR fluxes are proportional to the SFR when it is not too large, but fall off in the presence of a high SFR suggesting that the UIBs are destroyed by the UV field. However, in galaxies with a high SFR, there is an additional diffuse contribution (i.e. not well correlated with HII regions or H_{α} sources) to the $15\,\mu$m flux from very small, three-dimensional, grains. As a consequence, MIR dust emission is not an optimal tracer of star formation in normal, late-type galaxies, and MIR luminosities are better correlated with FIR luminosities than with more direct tracers of the young stellar population such as the $H\alpha$ and the UV luminosity. This conclusion, valid for nearby normal, late-type galaxies, may not apply to luminous starburst galaxies (Luminous Infrared Galaxies, or LIRGs), such as those detected in the ISO deep surveys (Förster-Schreiber et al. 2004). The MIR emission traces well the FIR and bolometric emission (Boselli et al. 1998; Elbaz et al. 2002).

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[3] The Unidentified Infrared Bands (UIB) dominate the 5 to 12 micron MIR spectrum of a wide range of celestial sources, and are usually assumed to arise from polycyclic aromatic hydrocarbon molecules (PAHs).

2.2. THE COMA, FORNAX, HYDRA, HERCULES & OTHER NEARBY ($z < 0.1$) CLUSTERS

Located at much larger distance than Virgo, but with a much larger mass, Coma has often been a favourite observational target, also in the IR.

Wang et al. (1991) made optical identifications of a total of 231 IRAS point sources in the regions of the Fornax, Hydra and Coma clusters, and identified respectively 13, 29 and 26 cluster galaxies. They concluded that the cluster environment has no detectable influence on galaxy infrared properties. Bicay & Giovanelli (1987) came to the same conclusion, based on a sample of 200 FIR-emitting galaxies in seven nearby clusters (including Coma). However, they remarked that LIRGs were much less common in the clusters than in the field (see also Section 2.3).

The most distant cluster studied with IRAS was A2151 (aka Hercules, at $z = 0.036$). Out of 41 sources detected at 60μm in a 1.6×2.5 sq.deg. field, Young et al. (1984) correlated 24 with late-type spiral galaxies of the cluster remarking the total absence of IR emission from E and S0 galaxies. Odenwald (1986) found CO emission in 3 of the 9 most optically luminous galaxies in the spiral-rich Ursa Major I(S) galaxy group, seeking evidence for galaxy interactions in a cluster lacking an intra-cluster medium, but found little evidence that processes unrelated to the galaxies themselves had influenced their histories. Studying a sample of 200 galaxies in seven nearby clusters[4], Bicay & Giovanelli (1987) pointed out the absence of luminous IR galaxies (LIRGs, i.e. galaxies with $L_{FIR} > 10^{11}\,L_\odot$). The sample consisted almost entirely of IR normal galaxies ($L_{FIR} < 10^{10}\,L_\odot$) in contrast to the rather high percentage of LIRGs (20%) detected by IRAS in the field. Moreover, the lack of a strong correlation between galaxy HI content and IR emission led them to conclude that SFR is not enhanced by interaction with the ICM, and might even be quenched by it. On the contrary, the suppressed FIR-to-radio ratio of spiral galaxies found in rich clusters with respect to poor clusters (Andersen & Owen, 1995) seemed to suggest that ram pressure enhances the radio emission in rich clusters while galaxy-galaxy interactions play a more important role in poor clusters where velocity dispersion, and so encounter velocities, are smaller.

Quillen et al. (1999) observed 7 E+A galaxies plus one emission-line galaxy at 12 μm with ISOCAM. They found that E+A galaxies have mid- to near-IR flux ratios typical of early-type quiescent galaxies, while the emission-line galaxy had enhanced 12 μm emission relative to the near-IR. Galaxies with ongoing star formation have a different velocity

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[4] A262, Cancer, A1367, A1656 (Coma), A2147, A2151 (Hercules), and Pegasus

distribution in the cluster from galaxies with stopped SF, suggesting that the ongoing infall of field spirals into the cluster potential may first trigger and then quench star formation.

Further observations of Coma cluster galaxies in the MIR came from Boselli et al. (1998) and Contursi et al. (2001). They also observed the cluster A1367, located in the Coma supercluster, detecting, in total, 18 spiral/irregular galaxies in the MIR and FIR with ISO.

Confirming results found in Virgo galaxies, these authors concluded that most IR-detected Coma galaxies display diffuse MIR emission unrelated to their Hα emission. The aromatic carriers are not only excited by UV photons, but also by visible photons from the general ISM. When the UV radiation field is too intense, it can even destroy the aromatic carriers, and overall the MIR emission is dominated by photo-dissociation regions rather than HII-like regions. A cold dust component was detected in all galaxies, at temperature of ~ 22 K, more extended than the warm dust. Only a very weak trend was found between the total dust mass and the gas content of the galaxies, even if some galaxies are very HI-deficient, and there was no detection of any relation between the MIR/FIR properties and the environment.

All these results seemed to suggest very little (if any) dependence of the IR properties of galaxies on the environment. If anything, IR emission was thought to be quenched in the cluster environment. However, only nearby clusters had been studied, in which most of the galaxies are early type with little gas (and dust). With the launch of ISO it became possible for the first time to study galaxy clusters out to redshifts where a significant change in the composition of the cluster galaxy population had already been (Butcher & Oemler 1984) or was soon to be (Dressler et al. 1999) observed in the optical.

2.3. Galaxy clusters at intermediate redshift

ISO's mid-infrared camera, ISOCAM, with its vastly improved sensitivity and spatial resolution with respect to IRAS, has successfully observed several galaxy clusters out to redshifts at which significant evolution might be expected to occur. At the same time, while studies of galaxies in nearby clusters are frequently done by targeting galaxies selected at other wavelengths, distant clusters can be completely surveyed due to their smaller angular size, producing an unbiased sample of infrared-emitting galaxies. Published ISO observations to date for clusters at redshifts above 0.1 (Coia et al. 2004a, b; Biviano et al. 2004; Metcalfe et al. 2003; Duc et al. 2002, 2004; Fadda et al. 2000; Barvainis et al. 1999; Altieri et al. 1999; Lémonon et al. 1998 and Pierre et al. 1996) address seven clusters (see Table. 1) spanning the redshift range $0.17 < z < 0.6$ and yield MIR data for around 110 cluster galaxies, slightly over 40 of these seen at 15 μm, and the rest only in the 7 μm bandpass.

Table I. Clusters in the redshift range $0.17 < z < 0.6$ studied with ISOCAM. The content of the columns in the table is as follows: name and redshift of the cluster; number, respectively, of 15 μm-only, 7 μm-only, and 7-and-15 μm confirmed cluster sources detected in each case, and total number of MIR sources detected. Results are gathered from Coia et al. (2004a, b), Biviano et al. 2004, Metcalfe et al. (2003), Duc et al. (2002, 2004) and Fadda et al. (2000).

Cluster	z	No. 15 μm-0nly sources	No. 7 μm-0nly sources	No. 7-and-15 μm sources	No. all sources
A2218	0.175	5	18	4	27
A1689	0.181	3	20	9	32
A1732	0.193	-	4	0	4
A2390	0.23	1	11	3	15
A2219	0.228	3	-	-	3
A370	0.37	1	5	0	6
Cl0024+1654	0.39	13	-	-	13
J1888.16CL	0.56	6	-	-	6

Almost half of the cluster galaxies detected at 15 μm prove to be LIRGs. (At the higher redshifts of the above sample only LIRGs fall above the sensitivity limit of the observations.) About 60% of these cluster galaxies were detected in observations originally intended to study distant field galaxies via the gravitational lensing amplification of the foreground clusters (Metcalfe et al. 2003; Barvainis et al. 1999; Altieri et al. 1999), and which, being gnerally very deep spatially-oversampled measurements, were able to provide insights about the lensing cluster galaxy populations (Biviano et al. 2004; Coia et al. 2004a and b). Fig. 2, taken from Coia et al. (2004b) is a V-band image of the $z = 0.39$ galaxy cluster Cl0024+1564 overlaid with contours of an ISO 15 μm map. The capacity of ISOCAM to detect and assign MIR counterparts unambiguously to numerous galaxies in the field is evident.

The first published ISOCAM observations of a distant cluster were those of the $z = 0.193$ cluster A1732 by Pierre et al. (1996), which

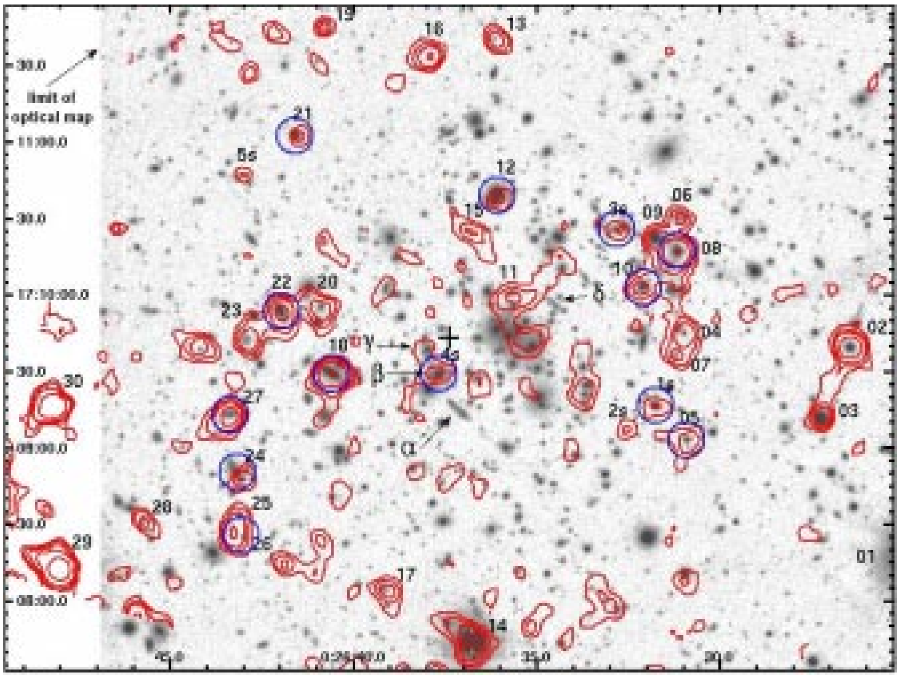

Figure 2. From Coia et al. (2004b): Contours of a 15 μm map of the (gravitationally lensing) galaxy cluster CL0024+1654 overlaid on a V-band FORS2 VLT image. 15 μm sources are numbered in order of increasing R.A. Dark circles identify spectroscopically confirmed cluster galaxies. Greek letters denote four prominent gravitational lensing arcs. North is up and East to the left, with the centre of the map falling at R.A. 00 26 37.5 and DEC. 17 09 43.4 (J2000).

they observed at 7 and 15 μm over an $8 \times 8\,\mathrm{arcmin}^2$ field. They found some evidence for a deficiency of spirals and star forming galaxies in the cluster, identifying only four cluster sources (at 7 μm, no cluster sources were detected at 15 μm) and 10 MIR galaxies in total in the field, most of them judged to be foreground. Nevertheless, these were the faintest MIR extragalactic sources reported up to that point and underlined the need for ultra-deep observations to detect cluster members at 15 μm.

Lémonon et al. (1998) reported evidence for an active star-forming region in a cooling flow (later 'cool-core') from 7 and 15 μm observations of the inner square arcminute of the well known lensing cluster A2390 ($z = 0.23$), with an attendant SFR of as much as $80\,M_{\odot}\,yr^{-1}$ in the central cD. But this was later found to be compatible with non-thermal emission from a jet associated with the cD (Edge et al. 1999). The estimated cluster mass deposition rates in cooling flows have since been lowered by one or two orders of magnitude (Böhringer et al. 2002).

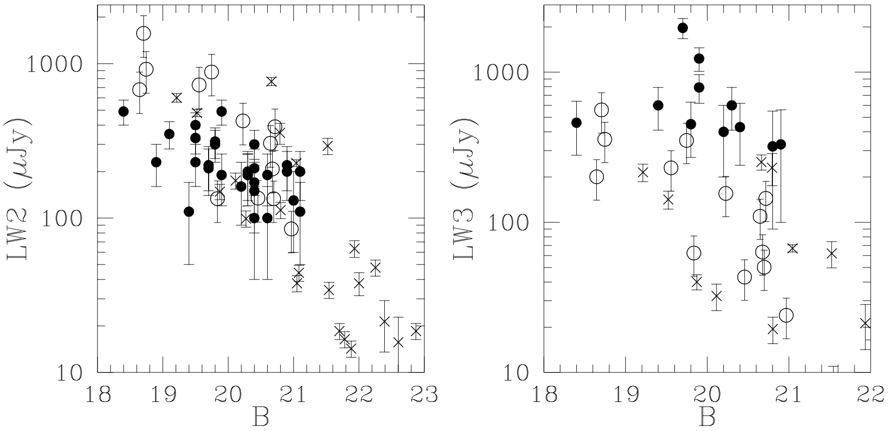

Figure 3. Fadda et al. (2000) found the [B_T - 7 μm] colour distribution of A1689 cluster galaxies (filled circles) to be compatible with that of the nearby Virgo (crosses) and Coma (empty circles) clusters, but the [B_T - 15 μm] colour distribution showed a systematic excess with respect to those nearer clusters. The cluster contains an excess of 15 μm sources relative to the field, suggesting that the environment of A1689 triggers starburst episodes in galaxies in the cluster outskirts that have similar IR luminosities and FIR/optical colours to those of field starburst galaxies.

A1689 ($z = 0.181$) was the first distant cluster for which detailed ISO observations were reported. Fadda et al. (2000) detected numerous cluster members (30 at 7 μm and 16 at 15 μm) within 0.5 Mpc of the cluster centre, and they found a correlation between the B-15 μm colour and cluster-centric distance of the galaxies. The 15 μm galaxies are blue outliers with respect to the colour/magnitude relation for the cluster and become brighter going from the center to the outer parts of the cluster. Coupled with the systematic excess of the distribution of the B-15 μm colours with respect to nearby clusters (Virgo and Coma), this suggested the existence of an IR analogue of the Butcher-Oemler effect in A1689 (see Fig. 3). A follow-up optical study of these infrared galaxies (Duc et al. 2002) showed that the morphology of the 15 μm sources in A1689 is generally spiral-like, with disturbances reminiscent of tidal interactions. No LIRGs were found in A1689. The highest total IR luminosity found for a cluster galaxy was $6.2 \times 10^{10} L_\odot$, corresponding to a SFR of $\approx 11\,M_\odot$ per year. The median SFR for A1689, derived from 15 μm measurements, was $2\,M_\odot$ per year, while the median found from [OII] (optical) measurements was only $0.2\,M_\odot$ per year.

This paper revealed the importance of IR observations in the study of star-formation in clusters. About one third of the 15 μm sources show no sign of star formation in their optical spectra. Moreover, comparing the star-formation estimates from IR and [OII] (see Fig. 4), Duc et

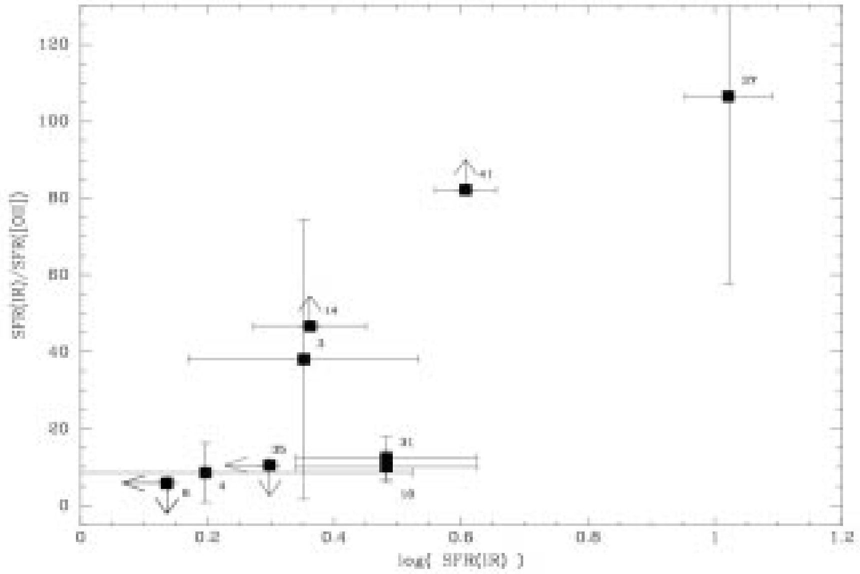

Figure 4. This plot, taken from Duc et al. (2002), compares the A1689 SFR derived from optical [OII] measurements, and from ISO MIR measurements. It illustrates the limitations of purely optical indicators of star formation rates. A major part, at least 90%, of the star formation activity taking place in Abell 1689 is hidden by dust at optical wavelengths.

al. (2002) deduced that at least 90% of the star formation activity taking place in A1689 is obscured by dust.

The ISO gravitational lensing survey programme (Metcalfe et al. 2003), and related work, led to deep observations of the core of several distant clusters. Large numbers of cluster galaxies were detected in the fields of A2218, A2390 and Cl0024+1654. So far, the cases of A2218 and CL0024+1654 have been treated in dedicated papers.

In the analysis of the galaxies in the field of A2218, a rich cluster at $z = 0.175$, Biviano et al. (2004) found 9 cluster members at 15μm inside a radius of 0.4 Mpc. In contrast to the case of A1689, which is at almost identical redshift ($z = 0.181$) and for which the median SFR is about $2M_{\odot}\, yr^{-1}$ and median L_{IR} is around $10^{10}\, L_{\odot}$, only one of the A2218 MIR galaxies is a blue Butcher-Oemler galaxy. The MIR luminosity of A2218 galaxies is moderate and the inferred star formation rate is typically less than $1M_{\odot}\, yr^{-1}$ with a median L_{IR} of only $6 \times 10^{8}\, L_{\odot}$. The absence of a MIR BO effect in A2218 might be a consequence of the small area observed, about 20.5 square arcminutes ($r < 0.4Mpc$), and yet the area studied for A1689 was not much larger, at about 36 square

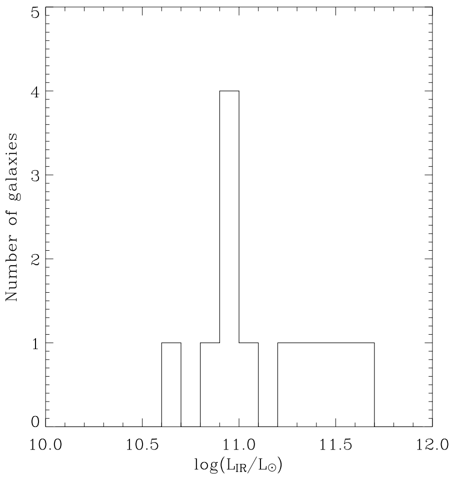

Figure 5. The infrared luminosity distribution for MIR galaxies in Cl0024+1654. The median value for L$_{IR}$ is $\sim 1.0 \times 10^{11}\, L_{\odot}$. (From Coia et al. 2004b.)

arcminutes. Coia et al. (2004b) suggest that the difference between these two clusters may be traced to their having different dynamical status.

The same sort of comparison can be drawn between the clusters Cl0024+1654 ($z = 0.39$) and A370 ($z = 0.37$). These two clusters at similar redshift and mapped in almost identical ways, exhibit very different numbers of LIRGs (Table 2), probably, according to Coia et al., because an ongoing cluster merger gives rise to enhanced star-forming activity in Cl0024+1654.

As can be appreciated from Fig. 5 taken from Coia et al. (2004b), the median infrared luminosity of ISO-detected cluster galaxies in Cl0024+1654 is around $1 \times 10^{11}\, L_{\odot}$. Star formation rates derived from the 15 μm data range from 8 to 77 $M_{\odot}\, yr^{-1}$, with median(mean) value of 18(30) $M_{\odot}\, yr^{-1}$.

Because of the different sky areas mapped with ISO for several of the clusters discussed here, and the different sensitivities achieved, it is not straightforward to compare the results for different clusters. A useful approach is to compare the number of LIRGs detected in each cluster, since these IR-bright galaxies would be expected to be seen for any of the observations considered. Such a comparison, taken from Coia et al. 2004b, is presented in Table 2. For each cluster an “expected” number of LIRGs is derived to test the hypothesis that the cluster is similar to the LIRG-rich cluster Cl0024+1654[5]. The LIRG count in

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[5] In fact, to avoid throwing away several sources close to the LIRG flux threshold of $1 \times 10^{11}\, L_{\odot}$ and thereby degrading the statistics of the comparison, the flux threshold for the comparison of detected luminous sources was set to $9 \times 10^{10}\, L_{\odot}$

Cl0024+1654 is multiplied by the ratios of (a) virial mass per unit area of the cluster to that of Cl0024+1654, the square of the respective distances to the cluster and to Cl0024+1654, and the observed solid-angle for the cluster to that of Cl0024+1654. The resulting column of the table can then be compared with the column listing the actual observed number of LIRGs for each cluster.

Table II. Summary of ISOCAM observations and results at 15 μm for five clusters of galaxies. The table is adapted from Coia et al. 2004b, and the data originates from Metcalfe et al. (2003) for Abell 370, Abell 2218 and Abell 2390, Fadda et al. (2000) and Duc et al. (2002) for Abell 1689, and Coia et al. (2004) for Cl 0024+1654. The content of the columns in the table are as follows: name and redshift of the cluster, total area scanned, sensitivity reported at the 5σ level, flux of the weakest reported source in μJy. Then number of cluster galaxies, total number of sources detected including sources without redshift and stars. virial radius of the cluster, virial mass, number of sources with $L_{IR} > 9 \times 10^10\,L_\odot$ detected and expected. The expected number of sources was obtained by comparison with Cl 0024+1654 as described in the text. Virial radii and masses are from Girardi & Mezzetti (2001) and King et al. (2002).

Cluster	z	Area	Sensitivity		n_sces^2		^{3}R$_{\rm vir}$	^{4}M$_{\rm vir}$	LIRGs^5	
		($'^2$)	(5σ)	min.^{1}	C	T			Obs	Exp
			(μJy)							
Cl0024	0.39	37.8	140	141	13	35	0.94	6.42	10	-
A370	0.37	40.5	350	208	1	20	0.91	5.53	1	8
A1689	0.18	36.0	450	320	11	18	1.1	5.7	0	1
A2390	0.23	7.0	100	54	4	28	1.62	20.35	0	1
A2218	0.18	20.5	125	90	6	46	1.63	18.27	0	1

[1] Faintest source considered in publication.

[2] Number of cluster sources, and total number of IR sources.

[3] Cluster virial radius (h^{-1} Mpc)

[4] Cluster virial mass ($h^{-1}\,10^{14}\,M_\odot$)

[5] Number of LIRGs (or near LIRGs ($L_{IR} > 9 \times 10^{10}\,L_\odot$) detected vs. number expected if cluster were to be similar to Cl0024+1654.

The two most distant clusters observed with ISO are CL0024+1654 ($z = 0.39$, Coia et al. 2004) and J1888.16CL ($z = 0.56$, Duc et al. 2004). These are among the deepest ISOCAM observations and could detect several cluster members. (For Cl0024+1654, 13 out of 35 sources found at 15 μm are spectroscopically confirmed to be cluster sources.

For J1888.16CL, 6 out of 44 sources found at 15 μm are so confirmed.) A common feature of these two clusters is the high star formation rate inferred from their MIR luminosities. These two observations were also the most extended cluster maps performed in terms of absolute cluster area covered at the cluster, 2.3 × 2.3 and 1.3 × 6 square Mpc for CL0024+1654 and J1888.16CL, respectively. This fact, and evolutionary effects detectable around $z \sim 0.5$ (see Dressler et al. 1999), may explain the high IR luminosity of the 15 μm sources found in these clusters.

In the case of J1888.16CL, Duc et al. (2004) estimate star-formation rates ranging between 20 and 120 $M_\odot$ per year. At least six galaxies belong to the cluster and have IR luminosities above $1.3 \times 10^{11} L_\odot$. In CL0024+1654, Coia et al. (2004b) report ten sources brighter than $9 \times 10^{10} L_\odot$. The star formation rates inferred from the MIR flux are one to two orders of magnitudes greater than those based on the [OII] flux (though in this case the comparison was only possible for the three sources for which [OII] data was available.) This is compatible with the result in A1689 (Fig.4) and implies similar dust extinction characteristics.

Interestingly, the galaxies emitting at 15μm appear to have a spatial distribution and a velocity dispersion slightly different from the other cluster galaxies. Galaxies in CL0024+1654 are detected preferentially at larger radii, with the velocity dispersion of 15μm sources being greater than that of the galaxies in the cluster. In J1888.16CL, Duc et al. (2004) estimate that to explain the number of sources detected on the basis of infall of galaxies from the field an infall rate of about 100 massive galaxies per 100 Myr is required, which seems unrealistic. Numerical simulations and X–ray observations show however that accretion onto clusters from the field is not a spherically symmetric process, but occurs along filaments or via mergers with other groups and clusters. One therefore cannot exclude the possibility that the LIRGs observed in these distant clusters belonged to such a recently accreted structure. An alternative possibility is that the collision with an accreted group of galaxies stimulated star formation in the galaxies of the group as a consequence of a rapidly varying tidal field (Bekki 1999). This could be the case for CL0024+1654 and A1689, clusters which show evidence of accreting groups of galaxies in their multi-modal velocity distributions. CL0024+1654 is in the process of interacting with a smaller cluster.

2.4. A DIFFUSE INTRA-CLUSTER DUST COMPONENT ?

The hot intra-cluster material contains metals, and so is not entirely primordial. Might not the stars which produced the metals also have deposited dust in the ICM? The first to note that emission from intra-cluster material might be observable were Yahil & Ostriker (1973), based on a galactic dust-to-gas ratio and the observed intra-cluster gas. Ostriker & Silk (1973) and Silk & Burke (1974) developed expressions for the lifetime of dust in a hot intra-cluster medium. Pustilnik (1975), drawing upon contemporaneous reports of optical absorption in clusters, attributed it to dust and estimated that cluster emission at 100 μm would be in the 10^3 to 10^4 Jy range for 6 nearby clusters. Voshchinnikov & Khersonskii (1984) also attributed claimed reddenning of galaxies in distant clusters to dust absorption, and estimated that the total FIR emission from the Coma or Perseus clusters should be 10^5 to 10^6 Jy (tens of Jy/arcminute^2) in the 50 to 100 μm range. They estimated the sputtering lifetime of intra-cluster dust grains to be up to 10^8 years. Hu et al. (1985), noting that intra-cluster dust must be short-lived, predicted FIR dust emission of a few Jy per square degree, close to the IRAS limit, for a sample of X-ray luminous clusters.

IRAS measurements failed to bear out even the most modest of the above predictions. Kelly & Rieke (1990) co-added IRAS scans across 71 clusters with $0.3 \leq z \leq 0.92$ to arrive at an average 60 μm value for cluster emission of 26±5 mJy per cluster, and 46±22 mJy at 100 μm. Dwek et al. (1990) refined models of intra-cluster dust and its interactions and calculated an upper limit of 0.2 MJy/sr for dust-emission from the Coma cluster, consistent with IRAS observations. Then total cluster emission would not be more than a few Jy at the peak wavelength (around 100 μm). They concluded that dust in the cluster centre could not explain the visual extinction, nor could cluster galaxies or their halos. Dust in the outskirts could, if it were un-depleted. But they saw no mechanism for the production of such dust. Wise et al. (1993) analysed 56 clusters at 60 and 100 μm from clusters with a range of X-ray emission, and some without cDs. For the only two clusters (A262 and A2670) showing a far-infrared excess lacking an immediate explanation (in terms of point sources or cirrus) they concluded that the result was likely to be due to discrete sources in the clusters. Averaged over the sample as a whole there was evidence of excess FIR at the 2-σ level. No large FIR excesses associated with cooling flows were found. Bregman et al. (1990) looked for evidence of star formation in 27 cD galaxies. In half of their sample of X-ray-bright clusters they found IR, X-ray and blue luminosities to be comparable, consistent with dust grains heated by the X-ray emitting gas, thereby suggesting that dust cooling can compare with thermal bremsstrahlung as a cooling mechanism for the intra-cluster gas.

Cox et al. (1995) studied a much larger sample of 158 Abell clusters, again at 60 and 100 μm, and after making a more rigorous correction for spurious sources due to galactic cirrus, they concluded that only about 10% of cD galaxies in rich clusters have significant FIR emission, but with luminosities ten times greater than the X-ray luminosities produced in the cores of clusters, a condition which they therefore regarded as transient for any individual cluster. If the FIR emission comes from dust heated by the intra-cluster thermal electrons, significant dust sputtering is expected on timescales of several 10^8 years. Dust must then be replenished to account for continuous IR emission, presumably through the mechanisms discussed for stripping material from cluster galaxies (see Section 1).

By the launch of ISO one could imagine a "life-cycle" of dust in a cluster, tracing the flow of material - gas and dust - out of infalling galaxies, the destruction of dust in the high-temperature intra-cluster medium, and its possible eventual re-deposition, through the mechanism of cooling flows, into the cluster-dominant galaxies. But only upper-limits or occasionally, and with marginal significance, global or average cluster FIR emission, could constrain scenarios for the role of dust in the physics of the clusters as a whole.

Stickel et al. (1998, 2002) used ISOPHOT to observe extended FIR emission of six Abell clusters. Strip scanning measurements were performed at 120 μm and 180 μm. The raw profiles of the $I_{120\,\mu m}/I_{180\,\mu m}$ surface brightness ratio including zodiacal light show a bump towards Abell 1656 (Coma), dips towards Abell 262 and Abell 2670, and are without clear structure towards Abell 400, Abell 496, and Abell 4038. After subtraction of the zodiacal light and allowance for cirrus emission, only the bump towards Abell 1656 (Coma) is still present (Fig. 6). This excess of $\approx$ 0.2 MJy/sr seen at 120 μm towards Abell 1656 (Coma) is interpreted as thermal emission from intra-cluster dust distributed in the hot X-ray emitting Coma intra-cluster medium. The integrated excess flux within the central region of $10'$ to $15'$ diameter is $\sim$2.8 Jy. Since the dust temperature is poorly constrained only a rough estimate of the associated dust mass of $M_D \sim 10^7\,M_\odot$ can be derived. The associated visual extinction is negligible ($A_V \ll 0.1$ mag) and much smaller than claimed from optical observations. No evidence is found for intra-cluster dust in the other five clusters observed.

Quillen et al. (1999) suggested integrated emission from the cluster galaxies as the most likely source for the detected signal at the centre of Coma. Stickel et al. (2002) replied that if this was indeed the case, the same signal should have been detected in *all* clusters observed.

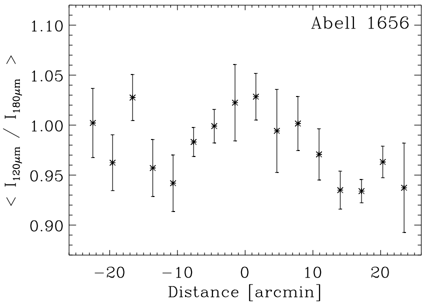

Figure 6. From Stickel et al. (2002): The overall zodiacal-light-subtracted surface brightness ratio $I_{120\,\mu m}/I_{180\,\mu m}$ for A1656 (Coma) averaged over both scan position angles and all detector pixels.

The absence of any signature for intra-cluster dust in five clusters and the rather low inferred dust mass in Abell 1656 indicates that intra-cluster dust is probably not responsible for the excess X-ray absorption reported in cooling flow clusters (White et al. 1991). These observations thus represent a further unsuccessful attempt to detect the presumed final stage of the cooling flow material. This agrees with numerous previous studies at other wavelengths, while spectroscopic observations with ESA's XMM-Newton X-ray observatory have shown that intra-cluster gas does not cool beyond ~ 1 keV (see, e.g., Molendi & Pizzolato 2001), so dust deposition in cooling flows is not actually expected. Not surprisingly, then, further attempts by Hansen et al. (1999, 2000a, b) also failed to detect dust associated with the cooling flows presumed to exist at the centres of most galaxy clusters.

3. Conclusions

Building upon the legacy of IRAS, ISO could consolidate a number of important fundamenatal conclusions about the properties of galaxies in the Virgo, Coma and other nearby galaxy clusters. The correlation between galaxy Hubble type and mid- and far-infrared properties was firmly established. A major new cold dust component was identified by ISOPHOT observations, which could not have been found by IRAS. Moderate resolution FIR spectroscopy was possible for Virgo cluster galaxies using LWS, establishing a correlation between the strength of the [CII] line and the FIR flux and a two order of magnitude difference in [CII] to near-IR ratio between early type galaxies and late (spiral) types. Mid-infrared emission (5 to 18 μm) was found to correlate with star formation, but to trace it less faithfully when star formation rates become high enough for UV photons to disrupt the infrared-emitting materials. However, the MIR emission traces well the FIR and bolometric emission. In general the properties of galaxies in nearby clusters ($z < 0.1$ were found to exhibit little dependence on the cluster environment.

ISO, for the first time, could extend mid-infrared observations to clusters beyond z = 0.1, and in so doing has detected over 100 galaxies in clusters in the redshift range 0.17 to almost 0.6. Although the collected observations on seven such clusters were rather heterogeneous, a number of important trends are found in the ISO results. There is a clear tendency for clusters at higher redshift to exhibit higher average rates of star formation in their galaxies, and numerous LIRGs have been observed in such clusters. There is tentative evidence for an association between the infrared luminosities found and galaxy infall from the field, but substantial evidence to link high levels of star-formation in cluster galaxies to the dynamical status of a cluster, and to interactions with other (sub-)clusters. It seems clear that star formation rates deduced for cluster galaxies from optical tracers often fall one to two orders of magnitude below rates derived from MIR emission levels, so that star formation in cluster galaxies may have been seriously underestimated in some cases, in the past.

ISO found little evidence for widespread infrared emission from dust in the intra-cluster medium.

Clearly, what ISO has not been able to supply has been systematic large area mapping of a substantial sample of galaxy clusters out to high redshift. Observing times to achieve such coverage with ISO would have been prohibitive, given the multi-position and heavily-overlapped rasters that would have been required. If galaxy evolution within clusters is to be further explored and related to galaxy evolution in the field, clusters of different masses and dynamical status must be studied systematically in the MIR and FIR out to well over 1 virial radius in order to understand how and why the IR properties of galaxies change from cluster to cluster, and from cluster to field. Large area coverage is important since it is known that significant modifications of the galaxy properties already occur in the outskirts of galaxy clusters (Gómez et al. 2003; Kodama et al. 2001; Lewis et al. 2002).

Several programmes underway or planned with the Spitzer Space Observatory should thoroughly address these challenges.

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