IRAS sources in the direction of rich clusters of galaxies

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SUMMARY

Results of a search for possible associations between point sources in the IRAS catalogue and rich clusters of galaxies in the recently published Abell, Corwin & Olowin (ACO) catalogue are presented. It is found that the surface density of IRAS sources rises progressively above the background as the projected distance from the cluster centre decreases below about 1 Mpc. The increase is most pronounced for the poorest clusters in the ACO catalogue. At low redshift ($z \leq 0.03$) the spatial distribution of ACO–IRAS associations is markedly anisotropic with a 3σ enhancement in the direction of the Great Attractor.

Key words: galaxies: clustering – infrared: galaxies.

1 INTRODUCTION

Early far-infrared (FIR) observations (wavelengths ranging from around 10–100 μm) showed that most FIR sources were associated with spiral galaxies and stars. Subsequent FIR studies have tended specifically to avoid clusters of galaxies (Lawrence et al. 1986) because it is well known that the fraction of spiral galaxies falls dramatically near the centres of clusters (Dressler 1980; Whitmore & Gilmore 1991). Investigations of small selected samples of clusters (Bicay & Giovanelli 1987; Leggett et al. 1987; Andernach et al. 1988; Meurs & Harmon 1988; Reuter & Andernach 1990; Wang et al. 1991) and studies of the large-scale distribution of FIR sources (Strauss & Davis 1988), however, suggest that clusters may contain significant numbers of FIR sources. Despite this, there has been no systematic study of FIR sources in clusters of galaxies.

In this paper I look for possible associations between rich clusters of galaxies and FIR sources detected by the Infrared Astronomical Satellite (IRAS). Two relationships are examined: the variation of normalized surface density of possible ACO–IRAS associations with projected distance from the cluster centre, and the spatial distribution of these associations at low redshift.

2 DEFINITION OF THE SAMPLE

The two catalogues used in this search are the IRAS point-source catalogue (Helou & Walker 1988a) and the Abell, Corwin & Olowin (ACO) rich-cluster catalogue (Abell, Corwin & Olowin 1989). As the primary aim of this study was to produce a finding list rather than a complete sample of FIR galaxies in the direction of Abell clusters, statistical results derived from this sample should be treated with caution.

2.1 The ACO catalogue

The ACO catalogue is composed of three sections: a new rich southern catalogue, a revised edition of the earlier rich northern catalogue (Abell 1958) and a supplementary catalogue of poorer and more distant clusters. There is an overlap region between the northern and southern catalogues in the declination range $-27^\circ < \delta < -17^\circ$. In this paper, the terms ‘north’ and ‘south’ will not refer strictly to the cluster declination but rather to the catalogue in which the clusters are listed.

Clusters in the catalogue are classified in several ways according to morphology, distance and richness of the cluster. The richness class, $R$, in particular, is rather ambiguous. Values of $R$ range from 0 (the poorest clusters) to 5 and are based on the number of galaxies found with magnitudes between $m_1$ (the magnitude of the third brightest cluster galaxy) and $m_3 + 2$ within 1.71 arcmin/pc kpc of the cluster centre, where $z$ is the estimated cluster redshift. In the northern and southern rich-cluster catalogues, the class $R = 0$ denotes a galaxy count between 30 and 49 (Abell et al. 1989), whereas in the supplementary catalogue it denotes a count less than 30. Thus $R = 0$ clusters are poorer in the supplementary catalogue than in the rich.

The term ‘rich’ clusters will be used to refer to all 4076 clusters listed in either the northern or southern rich catalogues. The two catalogues are nominally complete for clusters with redshifts $z$ in the range $0.02 < z < 0.2$ and $R \geq 1$, but have non-uniform sky coverage, particularly at low Galactic latitudes (Batuski et al. 1988). The term ‘poor’...
clusters will be used to denote the subset of 933 $R=0$ clusters in the supplementary catalogue. The sky coverage of the supplementary clusters is not uniform or complete in any way.

2.2 The IRAS data base

The IRAS data base covers 96 per cent of the sky and consists of observations in four infrared wavebands: 12, 25, 60 and 100 $\mu$m. Two catalogue were created from the IRAS data base: a point-source catalogue (Helou & Walker 1988a) consisting of sources with angular size $< 8$ arcmin (FWHM) which is used here, and a catalogue of slightly extended sources (Helou & Walker 1988b). The flux density limits are about $S = 1.5 \text{ Jy at 100 } \mu\text{m}$ and $S = 0.5 \text{ Jy at the shorter wavelengths.}$

To minimize contamination due to stars and Galactic sources, selection was made in the 60-$\mu$m band where almost all IRAS point sources are galaxies (Rowan-Robinson 1989, 1991) and the Galactic latitude was restricted to $|b| > 20^\circ$. The total sky coverage, not including the 4 per cent incompleteness quoted in the catalogue, is 8.3 steradians.

2.3 The sample

The final sample for this study of the distribution of IRAS sources in the direction of rich clusters contains 59498 IRAS sources and 3979 (1310 southern and 2669 northern) rich ACO clusters with $|b| > 20^\circ$. A finding list was created by cross-correlating the two lists as described in Section 3.

The results were then analysed in two ways:

(i) the surface density of IRAS sources was examined as a function of projected distance from cluster centres, and

(ii) the spatial isotropy of ACO–IRAS associations was investigated at low redshift.

A colour limit of $S_{25\mu m}/S_{60\mu m} < 1.5$ was applied in (i) (Section 3.1) to further reduce any residual stellar contamination (see Meurs & Harmon 1988; Rowan-Robinson 1988).

3 SEARCH FOR POSSIBLE CLUSTER–FIR ASSOCIATIONS

Catalogue cross-correlation can be an effective way to find possible associations for large numbers of sources. However, the influences of selection criteria and catalogue incompleteness need to be considered when interpreting results. The method used here to study the FIR associations with clusters of galaxies is essentially the same as that used by Andernach & Andreazza (1990) and Robertson & Roach (1990; hereafter RR) to investigate cluster–radio-source associations. The angular separation between each cluster centre and each 60-$\mu$m IRAS source is calculated and converted to a projected separation, $r$, using a cluster redshift estimated from the magnitude of the tenth brightest cluster member (Abell et al. 1989) and an Einstein–de Sitter model. Each cluster–IRAS–source pair with $r < r_{\text{max}}$, where $r_{\text{max}}$ is a predetermined maximum projected separation, is then listed. For consistency, the magnitude-based cluster redshift estimate is used even in cases where the actual cluster redshift has been measured directly.

$H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used throughout.

A comparison between the results of RR (using an incomplete sample) and Unewisse & Hunstead (1991) (using a complete subset of the RR sample) indicates that this form of cluster–object analysis is reasonably insensitive to the completeness of the sample. Some idea of selection effects in the present analysis may be obtained by comparing the redshift distributions of the two samples. The redshift distribution of rich clusters in the ACO spans the range $z = 0.01–0.26$, with a broad peak in the region $0.12–0.18$, whereas redshifts of galaxies associated with IRAS sources appear to peak at $z = 0.04–0.06$ (Meurs & Harmon 1988; Strauss & Davis 1988; Allen et al. 1990). Thus any resulting ACO–IRAS associations will be dominated by lower redshifts unless there happens to be a greatly enhanced correlation between high-redshift clusters and FIR-luminous galaxies, such as those studied by Woltencroft et al. (1988) and Golombek, Miley & Neugebauer (1988).

3.1 Surface density distribution

One way to test whether a given FIR detection is associated with a cluster is to compare its measured redshift with that of the cluster. On the other hand, if redshifts are not available, cluster association may be determined statistically by plotting the normalized surface density of FIR sources, $\sigma$, against $r$ out to large values of $r_{\text{max}}$. Here I use this latter method with $r_{\text{max}} = 3$ Mpc, or $2R_A$ where $R_A$ is an Abell radius as defined in Abell (1958), and look for deviations from a background level which is assumed to be uniform (see Section 3.2).

Results for the combined northern and southern ACO catalogues (i.e. rich clusters) are shown in Fig. 1(a). The normalization is relative to the 3979 clusters searched, so that $\sigma$ is actually the surface density per cluster per Mpc$^2$. A progressive and significant rise above the background is seen in Fig. 1(a) for $r < 1$ Mpc. This trend is similar to, but much weaker than, that seen for cluster–radio-source associations by RR and Unewisse & Hunstead (1991). The significance of the rise was tested by rerunning the correlation program with artificial cluster positions offset from the ACO values by $2^\circ$ in declination and $2^\circ$ in right ascension: no sign of a central peak was found and the surface density was consistent with the background rate shown in Fig. 1(a).

3.2 Modelling the data

Two models for the surface density distribution were fitted to the data in Fig. 1(a) using the Powell method and a tolerance level of around $10^{-6}$ (Press et al. 1987)—the Hubble (1930) model:

$$\sigma = (a_0 - b)(1 + (r/r_c))^2 + b,$$

and the King (1962) model:

$$\sigma = (a_0 - b)(1 + (r/r_c))^{-1} + b,$$

where $a_0$ is the central surface density, $b$ is the background density and $r_c$ is the core radius where the surface density drops to half the central density. An attempt was made to fit the distribution using the de Vaucouleurs (1948) $r^{1/4}$ function but the effective radius was found to be so sensitive to the choice of background level that the model was not considered further.
The parameter values obtained for rich clusters using the King and Hubble models are compared in Table 1 along with a reduced $\chi^2$ ($\tilde{\chi}^2$) for assessing the goodness of fit. The fitted peak is slightly different in the two models, due to the fact that the Hubble function contains a central cusp and the King does not.

The rise in the surface density of IRAS sources does not appear to be simply a function of the underlying galaxy distribution. The optical core radius of a cluster is $\approx 1/12 R_A$ or 125 kpc (Sarazin 1988), whereas the IRAS core radius is $\approx 1/3 R_A$ in both the King and Hubble models (480 kpc for the King and 430 kpc for the Hubble). Furthermore, studies of galaxy–cluster correlations show no evidence of a peak in the amplitude of the spatial cross-correlation function as $r$ approaches the cluster centre (Lilje & Efstathiou 1988).

The King model is shown fitted to the data in Fig. 1(a). The fit to the central region of the cluster is poor but still consistent with the Poisson errors.

### 3.3 Sky distribution

Having established that there is a significant excess of IRAS sources in the direction of rich clusters, a finding list of potential ACO–IRAS associations was compiled by selecting 60-μm IRAS sources with $r \leq 500$ kpc ($\approx r_c$ for the King and

IRAS sources towards rich clusters

<table>
<thead>
<tr>
<th>Table 1. Model parameters for rich clusters.</th>
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<tr>
<td></td>
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<tr>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Hubble</td>
</tr>
<tr>
<td>King</td>
</tr>
</tbody>
</table>

Hubble models. The list contains 168 IRAS sources in 100 southern clusters and 188 sources in 143 northern clusters.

Because a metric search area has been defined, the number of chance associations in each cluster will depend on the cluster redshift. The mean surface density of 60-μm IRAS sources is $7196 \pm 30$ sr$^{-1}$ for $|b| > 20^\circ$. Assuming the sources are distributed uniformly over the sky, an estimate of the number of genuine ACO–IRAS associations for each cluster can then be made by subtracting the expected number of chance associations. The uncertainty in the background count is negligible. There will, of course, still be some residual distance-dependent selection effects (e.g., less powerful sources can be detected in the nearest clusters) which can be overcome in part by restricting the redshift interval.

Fig. 2 shows the northern and southern sky distributions of ACO–IRAS associations in Lambert projection (Richardus & Adler 1972) and B1950 coordinates for the 35 clusters with estimated redshifts $z \leq 0.03$. The excess numbers of associations above the background ($\rho$) are represented as circles centred on each cluster with area $\propto \rho$. The figure is dominated by three southern clusters, namely A3526 (Centaurus), with 11.5 ± 4.2 IRAS detections, A3565 (11.1 ± 3.8 detections) and A3574 (10.5 ± 4.2 detections). These three clusters have more IRAS associations than any of the better known clusters which have been the subject of FIR study (Bica & Giovanelli 1987) such as Hydra (A1060, 5.1 ± 2.8 detections), Coma (A1656, 2.7 ± 2.0 detections), and Hercules (A2151, 3.0 ± 2.0 detections). Although A3526, A3565 and A3574 have each been the subject of optical investigations, they are unexplored in the infrared where further investigation is clearly demanded.

The clusters which dominate Fig. 2 fall in the direction and redshift range of the so-called ‘Great Attractor’ (GA; Lynden-Bell et al. 1988) which is marked by a star in Fig. 2. This localized enhancement of ACO–IRAS associations is discussed further in Section 4.2.

### 4 DISCUSSION

Two results of this work are discussed here, the unexpected excess of ACO–IRAS associations close, in projected separation, to cluster centres and the apparent local anisotropy in the direction of the GA.

#### 4.1 Excess surface density

Can we say which galaxies are responsible for the observed rise in $\sigma$ with decreasing $r$? A $\chi^2$ test was performed on the sample comparing the properties of clusters containing an IRAS source with the overall cluster properties in the ACO catalogue. Two different correlations were found to be significant ($p < 0.05$ that the result is due to chance): (i) IRAS
O'Connell (1990) who found, in a sample of X-ray bright clusters, that 46 per cent of cD galaxies were detected in the FIR. Evidence that the spirals may be contributing to that observed FIR emission is supported by the work of Hickson, Menon & Persic (1989), who found that spiral galaxies in groups have an enhanced probability of producing FIR emission.

When the rich sample is sub-divided into richness classes, it is clear that the major contribution to the peak seen in Fig. 1(a) comes from the poorest clusters (richness class $R = 0$). If the less-rich clusters in the 'rich' cluster portion of the ACO strongly influence the shape of Fig. 1(a), it might be expected that a similar graph of $\sigma$ versus $r$ for the 953 poor clusters ($R = 0$) in the supplementary catalogue of the ACO would exhibit an even more significant rise above background. Fig. 1(b) confirms this conjecture, showing a stronger and narrower central peak for poor clusters. Significantly, 81 per cent (756) of the poor clusters contain IRAS sources, as opposed to 7.2 per cent of the rich clusters, with 596 clusters having more than one IRAS association. This high detection rate may also reflect the fact that the poor clusters have a redshift distribution which peaks at a lower value than the rich clusters, around $z = 0.08$, which is a better match to the IRAS redshift distribution.

A comparison of model parameters for poor clusters is given in Table 2. The values of $r_e$ (King: 115 kpc and Hubble: 105 kpc) are less than one-third the corresponding values obtained for the richer sample (Table 1). The difference in background levels between Figs 1(a) and (b) (0.07 for the rich and 0.18 for the poor) is a selection effect due to the fact that the poor clusters tend to lie nearby.

Given that both radio-source associations (RR) and FIR associations (this paper) are available for the same cluster sample, it seems opportune to look for any evidence of a radio–FIR correlation for galaxies in these clusters. It is generally accepted that a radio–FIR correlation exists for low radio power, infrared-selected spiral galaxies (Wunderlich, Klein & Wielebinski 1987; Unger et al. 1989). Some evidence for an extension of this correlation to higher radio power sources, similar to those considered by RR, has been found by Golombek et al. (1988), but studies of such radio sources in clusters have found very few to be FIR emitters (Andernach et al. 1988; Reuter & Andernach 1990). The FIR sample in this paper supports the latter results, with no correspondence being found between IRAS and the 408-MHz sources with $r \leq 500$ kpc given in RR.

### Table 2. Model parameters for poor clusters.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_0$ [Mpc$^{-2}$]</th>
<th>$r_e$ [kpc]</th>
<th>$b$ [Mpc$^{-2}$]</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble</td>
<td>1.18</td>
<td>105</td>
<td>0.183</td>
<td>1.39</td>
</tr>
<tr>
<td>King</td>
<td>0.70</td>
<td>115</td>
<td>0.184</td>
<td>1.34</td>
</tr>
</tbody>
</table>

4.2 Local anisotropy

Large-scale streaming motions of local galaxies seem to be directed towards the Centaurus–Pavo region of the sky. Lynden-Bell et al. (1988) interpreted the peculiar velocity field as being due to the influence of a large mass concentration which has come to be known as the Great Attractor.

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\*Clusters are assigned one of five Bautz–Morgan classes (Bautz & Morgan 1970): BM I, I–II, II–III or III according to the degree to which they are dominated by one, usually centrally located, cluster member. BM I are completely dominated.
Table 3. Properties of dominant clusters in the direction of the GA.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>z_mea</th>
<th>R</th>
<th>BM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3526</td>
<td>0.010</td>
<td>0</td>
<td>I–II</td>
</tr>
<tr>
<td>A3565</td>
<td>0.019</td>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>A3574</td>
<td>0.014</td>
<td>0</td>
<td>I</td>
</tr>
</tbody>
</table>

(GA). The exact location and mass of the GA are still uncertain but recent results indicate that the centre lies near a redshift of 0.014 in the direction RA = 13°06′ ± 48", Dec. = −40°10′ (Faber & Burstein 1988). Fig. 2 shows a clear enhancement of ACO–IRAS associations in a region bounded by 12°30″ < RA < 14°4 and −45° < Dec. < −25° for clusters with redshifts z ≤ 0.03, that is, in the direction of the GA. In contrast, a plot of the distribution of all ACO clusters within z = 0.067 over the sky by Scaramella et al. (1989) did not show appreciable clustering in the direction of the GA. Furthermore, no evidence for excess IRAS associations is seen in the direction of other known mass concentrations such as the Pisces–Perseus (22° < RA < 0° and 0° < Dec. < +50°) or Coma superclusters (RA = 13°, Dec. ≈ 28°).

Comparing the number of associations per cluster searched we find that a cluster in the direction of the GA has on average 5 ± 1.2 associations with r ≤ 500 kpc, whereas the entire sample of 35 clusters has an average of just 2.2 ± 0.1 (a factor of 2.3 ± 0.6 less). The enhancement rises to a factor of 3.5 ± 0.4 if the comparison is made between the clusters in the direction of the GA and the rest (average 1.5 ± 0.3 associations per cluster). These results, however, must be treated with caution as: (i) there are only small numbers of clusters involved, and (ii) it is possible that the IRAS concentration found by Allen et al. (1990) in the same direction as the GA, but at a redshift of z = 0.05, may be increasing the number of chance alignments.

The origin of the enhancement of ACO–IRAS associations in the direction of the GA is unclear. Table 3 shows the measured redshift (z_mea), richness class (R) and BM class of the three southern clusters dominating Fig. 2. As expected, each of these clusters is nearby, poor and of BM class I or I–II. No difference is found between the average colour S_25μm/S_60μm of associations in the GA region (0.53 ± 0.04) and elsewhere (0.59 ± 0.02). A complete optical identification and redshift programme is required to investigate this question properly.

If we further restrict the redshift interval to z ≤ 0.02, where the GA is thought to lie, the anisotropy becomes even more significant but the total number of clusters (9) is then too small for firm conclusions to be drawn. Saunders et al. (1991) found no IRAS density enhancement in the direction of the GA. Thus one interpretation of the enhancement revealed by the present study is that ACO–IRAS associations may be better probes of local mass concentrations than IRAS sources alone.

5 CONCLUSIONS

The two major results from this investigation of IRAS point sources in the direction of rich ACO are as follows.

(i) 7 per cent of ACO rich clusters contain IRAS sources. In general these sources tend to lie close to the cluster centre and occur preferentially in the poorer and centrally dominated clusters. The cluster–FIR correlation is much stronger for the poorest ACO clusters from the supplementary catalogue, with more than 80 per cent containing IRAS sources.

(ii) Evidence for a significant enhancement in ACO–IRAS associations is found in the direction of the Great Attractor. This raises the possibility that cluster IRAS sources are effective tracers of deep gravitational potential wells.

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IRAS sources towards rich clusters


