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SEARCH FOR COLD GAS IN CLUSTERS WITH AND WITHOUT COOLING FLOWS

D. A. GRABELSKY AND M. P. ULMER
Department of Physics and Astronomy, Northwestern University
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ABSTRACT

The dominant galaxy in each of ~40 clusters has been studied using co-added *IRAS* survey data, and 11 of these galaxies have been observed for CO ($J = 1 \rightarrow 0$) emission with the NRAO 12 m telescope at Kitt Peak. Half of the galaxies in our sample are in clusters reported to have cooling flows, while the other half are not. Six of the galaxies appear to have been detected by *IRAS* with varying degrees of reliability, in addition to one previously known strong detection; all seven are reported to have cooling flows. None of the 11 galaxies observed was detected in CO emission. There is a possible, although weak, correlation between reported cooling flow rates and infrared luminosities, but no correlation between flow rates and derived ISM masses. No significant differences in the CO or IR properties are inferred between dominant galaxies in clusters with or without flows.

Assuming that cluster cooling flows with $\dot{M} \sim 100\ M_\odot\ \mathrm{yr}^{-1}$ exist and are feeding star formation in the central, dominant galaxies, then the star formation rates and efficiencies in these galaxies must be quite high in order to render the CO undetectable. At the same time, the infrared luminosities of these galaxies are unremarkable, suggesting that the correlation between star formation efficiency and infrared luminosity found for spirals does not apply to star formation in cooling flows. Alternatively, if cooling flows do not exist, or if the mass-flow rates have been overestimated, cluster-dominant galaxies could sit at the low end of the L_{CO}-L_{IR} relation found for spirals. A brief comparison with elliptical galaxies indicates that cluster-dominant galaxies and ellipticals have similar FIR properties.

Subject headings: galaxies: clustering — galaxies: intergalactic medium — galaxies: interstellar matter — infrared: sources

I. INTRODUCTION

In the last 15 years, X-ray observations of clusters of galaxies have led to the discovery that the hot intracluster gas in the cores of many clusters appears to be cooling on time scales short in comparison with the ages of the clusters (e.g., Fabian and Nulsen 1977; Stewart *et al.* 1984). If the X-ray emission is sustained for much longer than a cooling time without reheating of the gas, then the cooling gas will flow toward the cluster center as it is replenished by hot gas from the surrounding region (e.g., Cowie and Binney 1977; Fabian, Nulsen, and Canizares 1984). All of the clusters showing evidence for this phenomenon are characterized by a central, dominant galaxy (usually a cD) which is generally thought to be accreting the cooling gas. Inferred mass-flow rates ranging over 5–500 $M_\odot$ yr^{-1} (cf. Sarazin 1986), it is clear that substantial mass may be accreted onto the central galaxies in cooling flow clusters over the lifetimes of the clusters. However, while the presence of cooling gas in the cores of many clusters seems well established, there is some debate as to whether reheating of the cooling gas can be ruled out (Bertschinger and Meiksin 1986; Silk *et al.* 1986; Rosner and Tucker 1989; Tribble 1989), and it is not generally accepted that the existence of cooling accretion flows has been convincingly demonstrated.

An important question related to the existence of flowing, as opposed to simply cooling, gas is the ultimate fate of the accreted material. The most obvious and indeed generally assumed repository is stars. So far, the search for confirming evidence in the form of star formation has been guided in part by the theoretical prediction that low-mass stars will be formed preferentially in the high-pressure environment of cooling flows (Sarazin and O'Connell 1983; O'Connell and McNamara 1989). Regardless of the stellar mass spectrum, however, the cooling gas must pass through a cold, neutral phase, and perhaps a more fundamental test for the accumulation of cooling intracluster gas in cluster cores is the search for the cold gas that must feed the star formation. The observations we present in this paper are directed at detecting such a reservoir.

We co-added *IRAS* survey data about the central galaxy in each of 37 clusters and observed 11 galaxies, nine of which are a subset of our *IRAS* sample, with the NRAO[1] 12 m telescope at Kitt Peak for CO ($J = 1 \rightarrow 0$) emission. The total sample, consisting of Abell clusters (with one exception), was selected such that half of the galaxies are in clusters showing evidence for cooling flows while the other half are not. Our goal was to search for cold interstellar gas in these galaxies, with a focus on the possible contribution from accretion of the cooling intracluster gas. Seven of the galaxies appear to have been detected by *IRAS*, all but one at fairly low flux levels ($\gtrsim 3$ times the local signal-to-noise ratio). No CO emission was detected in any of the observed galaxies. If the galaxies we observed are in fact accreting matter at rates similar to the inferred cooling flow rates, then the star formation rates and efficiencies must be quite high; yet at the same time, the IR luminosities are observed to be fairly low. We present the observations in § II; our results are given in § III; discussion follows in § IV; our conclusions are given in § V.

[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

II. OBSERVATIONS

a) *The Sample*

The selection criteria for our sample was the reported evidence either for or against the existence of cooling flows in the clusters. Most of the sample was taken from the list of Stewart *et al.* (1984) of X-ray clusters observed with the *Einstein* observatory. Their analysis of the X-ray data from 36 clusters indicated that the intracluster media in about half have cooling times less than H_0^{-1}, the primary evidence cited in the case for the presence of a cooling flow. We included the Abell clusters from their list both with and without cooling flows, those without providing a "control" sample. Eight additional clusters with reported cooling flows were taken from Sarazin (1986, and references therein) and Romanishin and Hintzen (1988). Our sample is listed in Table 1. All redshifts are heliocentric and all distances in this paper use $H_0 = 50$ km s^{-1} Mpc^{-1}.

b) *IRAS Data*

We obtained one-dimensional co-added *IRAS* survey data for all but two of the galaxies in our sample using the

TABLE 1

CLUSTER SAMPLE

Cluster	R.A.[a]	Decl.	z^{b}	Distance (h_{50}^{-1} Mpc)	$\dot{M}^{c}$ ($M_{\odot}$ yr^{-1})
A85	0h39m18s	−9°34′21″	0.0553	334	100
A154	1 08 17	17 23 23	0.0607	370	...
A262	1 49 50	35 54 22	0.0161	97	28
A399	2 55 09	12 50 02	0.0723	435	...
A400	2 55 03	5 49 20	0.0230	139	2
A426	3 16 28	41 20 12	0.0172	103	300
A496	4 31 19	−13 21 57	0.0330	198	200
A576	7 17 23	55 51 30	0.0401	241	40
A592	7 39 54	9 29 53	0.0626	376	...
A671	8 25 27	30 36 02	0.0499	299	...
A957	10 11 05	−0 41 09	0.0444	264	...
A978	10 17 56	−6 16 56	0.0534	320	500
A1060	10 34 12	−27 14 36	0.0135	81	6
A1126	10 51 11	17 07 01	0.0832	499	500
A1185	11 07 56	29 02 41	0.0350	210	...
A1291	11 29 38	56 14 25	0.0586	352	...
A1314	11 32 07	49 20 44	0.0333	200	...
A1775	13 39 30	26 37 56	0.0717	430	...
A1795	13 46 34	26 50 28	0.0630	378	400
A1809	13 50 36	5 23 35	0.0790	474	...
A1890	14 15 12	8 25 00	0.0570	342	...
A1983	14 50 35	16 54 25	0.0456	274	7
A1991	14 52 14	18 50 42	0.0587	352	115
A2029	15 08 27	5 56 35	0.0776	466	250
A2040	15 10 20	7 37 42	0.0455	273	...
A2052	15 14 12	7 12 26	0.0350	210	120
A2063	15 20 39	8 47 14	0.0336	202	26
A2107	15 37 26	21 56 56	0.0417	250	18
A2124	15 43 05	36 16 31	0.0666	400	...
A2142	15 56 10	27 23 36	0.0906	544	28
A2199	16 26 55	39 39 38	0.0306	184	110
A2255	17 12 10	64 07 00	0.0739	443	...
A2256	17 06 31	78 47 29	0.0542	325	...
A2319	19 19 33	43 50 51	0.0539	323	75
A2593	23 21 48	14 22 00	0.0417	250	...
A2626	23 33 59	20 52 15	0.0554	332	10
A2657	23 42 25	8 55 02	0.0408	245	36
A2670	23 51 40	−10 41 51	0.0770	462	...
2A 0335+096	3 35 57	9 48 26	0.0350	210	280

[a] Galaxy coordinates are from Hoessel, Gunn, and Thuan 1980, except as follows: A426, A576, A592, A1060, A1314, and A2319 are from Peterson 1970; A1890 is from the *Morphological Catalogue of Galaxies* (Vorontsov-Velyaminov *et al.* 1974); A2593 is from the *Uppsala General Catalogue of Galaxies* (Nilson 1973); A2626 is from Hazard and Jauncey (1972); and A262, A400, A496, A1126, A1795, A1983, A2199, A2670, and 2A 0335+096 were measured directly from the Palomar Sky Survey plates with the two-axis Grant measuring engine at Kitt Peak National Observatory.

[b] Galaxy redshifts are from Hoessel, Gunn, and Thuan 1980, except as follows: A262, A576, A592, A1314, A2319 are from Peterson 1970; A426 and A2593 are from Humason, Mayall, and Sandage 1956; A1060 is from Faber and Dressler 1977; A1890 is from Struble and Rood 1986; A2626 is from Sargent 1973; and 2A 0335+096 is from Schwartz, Schwarz, and Tucker 1980. All redshifts from these references were adjusted (if necessary) to refer to the Sun.

[c] Mass-flow rates are from Stewart *et al.* 1984 except as follows: A426, A496, A576, A978, A1126, A2052, and A2142 are from Sarazin 1986, and references therein; and 2A 0335+096 is from Romanishin and Hintzen 1988. Ellipses indicate that there is no X-ray evidence for a cooling flow.

ADDSCAN and SCANPI processes at IPAC.[2] Two-dimensional co-adds were obtained for those sources which met the following criteria: signal-to-noise ratios (from the SCANPI program) of greater than 3, detection in at least two *IRAS* bands, and (one-dimensional) positional agreement with the galaxy of generally 1′ or better. This initial threshold provided candidate sources without regard for possible misidentifications or confusion, e.g., with nearby galaxies in the field, or cirrus. With one exception (NGC 1275), none of the galaxies were detected in either the 12 μm or 25 μm bands.

In order to reduce the chances of misidentifications among the candidate sources, the two-dimensional images were used to compare the IR source coordinates at 60 μm and 100 μm with each other and with the optical positions of the galaxies on the Palomar Sky Survey. The nominal tolerance for IR-optical source position agreement was $\sim 1'$ but was more stringent for crowded fields and somewhat less stringent (up to $\sim 1\farcm5$) for less crowded fields.

c) CO *Observations*

We observed 11 galaxies from our sample for CO ($J = 1 \rightarrow 0$) emission with the 12 m NRAO telescope at Kitt Peak. All but one, A1185, are reported to have cooling flows. The observations were carried out on 1987 October 26–28, 1988 June 17–18, 1988 June 28, and 1988 July 10. The 3 mm SIS receiver was used with both 256 × 2 MHz channel spectrometers in series for averaging the two polarization channels. The receiver was tuned to the redshifted frequency of the CO line. The velocity resolution was ~ 5.3 km s^{-1}, and the full velocity coverage was ~ 1330 km s^{-1}. Alternate source and reference spectra were obtained using the nutating subreflector.

Pointing was checked periodically using standard sources as near on the sky as possible to the galaxy being observed. The weather and sky brightness were highly variable during all of the runs, and system temperatures ranged from ~ 600 K to >1000 K. During the first run, improper calibration of the spectra, due to a previously undiscovered software error in the telescope computer system, forced us to discard all the data from one of the spectrometers and part of the data from the other.

III. RESULTS

a) *IRAS*

Our findings for the *IRAS* data are summarized in Table 2. Aside from NGC 1275 in Abell 426 (Perseus), which is already in the *Point Source Catalog*, six previously unreported sources appear to have been detected, although none of the six can be classified as an unquestionable detection. We ranked them, somewhat subjectively, on the basis of signal strength, quality of the SCANPI point-source fit to the scan profile, positional concidence of the 60 μm and 100 μm sources, and proximity to the optical image of the galaxy. Briefly, A1126 and A2199 are very probable detections, showing clear signals at 60 μm and 100 μm, and good positional agreement with the optical images ($\sim 1'$ for A2199, $\lesssim 0\farcm5$ for A1126). A2063, A576, and A400 are likely detections, the first two showing strong 60 μm and 100 μm signals but IR-optical positional agreements of $\gtrsim 1'$, and the third showing weaker 60 μm and 100 μm signals but better positional agreement. A1983 is a marginal detection.

TABLE 2

IRAS RESULTS

CLUSTER	FLUX DENSITY (mJy) 12 μm	25 μm	60 μm	100 μm	L_{IR} ($10^{10} L_\odot$)	M_{IR}[a] ($10^{10} M_\odot$)
A85	<84	<144	<135	<348	<4.89	<0.60
A154	<84	<147	<165	<420	<7.50	<0.93
A262	<114	<99	<63	<504	<0.42	<0.75
A399	<69	<138	<90	<1560	<22.2	<4.80
A400	<105	<72	121	432	0.83	0.14
A426	1050	3050	6250	7110	12.9	1.10
A496	<51	<51	<54	<456	<0.96	<2.91
A576	<78	<60	104	312	4.10	0.29
A592	<72	<126	<96	<360	<5.67	<0.84
A671	<123	<120	<111	<501	<4.29	<0.66
A957	<171	<102	<96	<375	<2.73	<0.42
A1060	<75	<129	<96	<750	<0.42	<0.09
A1126	<126	<156	137	929	9.04	1.90
A1185	<45	<93	<117	<609	<2.61	<0.42
A1291	<15	<78	<120	<249	<4.44	<0.48
A1314	<105	<93	<147	<381	<1.98	<0.24
A1775	<192	<114	<102	<276	<6.45	<0.81
A1795	<78	<75	<93	<405	<6.03	<0.93
A1809	<144	<186	<129	<345	<9.69	<1.23
A1890	<114	<114	<117	<372	<5.04	<0.69
A1983	<90	<84	80	680	2.83	0.82
A1991	<72	<111	<129	<393	<5.76	<0.81
A2029	<99	<114	<99	<255	<7.29	<0.90
A2040	<66	<114	<129	<1365	<8.01	<1.59
A2052	<72	<153	<24	<498	<1.59	<0.36
A2063	<82	<102	350	600	2.91	0.38
A2107	<51	<81	<93	<456	<2.82	<0.45
A2124	<72	<57	<69	<135	<3.24	<0.36
A2142	<82	<82	<105	<402	<13.2	<1.95
A2199	<69	<60	120	640	2.39	0.37
A2255	<42	<36	<75	<156	<4.59	<0.51
A2256	<48	<42	<108	<1230	<10.6	<2.13
A2319	<69	<72	<135	<600	<6.18	<0.99
A2593	<78	<105	<108	<363	<2.58	<0.36
A2626	<87	<156	<87	<360	<4.11	<0.63
A2657	<96	<123	<144	<636	<4.08	<0.63
A2670	<135	<162	<159	<417	<9.99	<1.41

[a] Derived mass in units of $M_\odot$ follows from Jura 1986: $M_{IR} = 1.6 \times 10^5 F_\nu$ (100 μm) D^2, where the 100 μm flux density is in Jy, and D is the distance in Mpc.

The IR-optical positions agree to $\sim 1'$, but the 60 μm signal-to-noise ratio is barely 3. For the remaining galaxies, upper limits to the flux densities of three times the local noise (taken from the SCANPI program) are given.

Infrared luminosities and dust temperatures were calculated following Appendix B[3] in *Cataloged Galaxies and Quasars Observed in the IRAS Survey* (1985), assuming the emissivities to go as λ^{-1}. For the seven galaxies detected, L_{IR} ranges from $0.83 \times 10^{10} L_\odot$ (A400) to $13 \times 10^{10} L_\odot$ (A426). Inferred dust temperatures for these galaxies were all less than 30 K except for A426 and A2063, for which $T_d = 40$ K, and A1126 for which $T_d = 36$ K. The 3 σ upper limits to L_{IR} given in Table 2 for the remaining galaxies were derived based on an assumed value of 3.16 for the ratio of F_ν (100 μm)/F_ν (60 μm). They range from $0.33 \times 10^{10} L_\odot$ to $22 \times 10^{10} L_\odot$. The median L_{IR} (detections and upper limits) is roughly $4.5 \times 10^{10} L_\odot$.

[2] IPAC is funded by NASA as part of the *IRAS* extended mission program under contract to JPL.

[3] The values given in Table B.1 of R, the ratio of flux from 1–500 μm to that in the 60 μm plus 100 μm windows, versus $C (\equiv F_\nu [100\,\mu m]/F_\nu [60\,\mu m])$ were interpolated for all detected sources except A1983 ($C = 8.5$), for which a linear extrapolation from the highest three tabulated values of C was used. Dust temperatures were also derived from Table B.1 by fitting an exponential to the tabulated values of T_d versus C.

An ISM mass or (3 σ) mass upper limit was determined for each galaxy from the 100 μm flux densities (or flux density upper limits) following equation (5) in Jura (1986). The values for the detected galaxies range from $1.4 \times 10^9 M_\odot$ (A400) to $1.9 \times 10^{10} M_\odot$ (A1126). A number of assumptions go into Jura's derivation of gas mass from 100 μm flux density, notably, a dust temperature of 20 K, and a gas-to-dust ratio of 100. The derived mass, being inversely proportional to the Planck function, is very sensitive to the dust temperature. In the absence of any spatial information, the assumption of a uniform dust temperature of 20 K in Jura's derivation is a reasonable one for early-type galaxies (see Jura 1982), so we adopt it here, even though the 60 μm and 100 μm flux densities of some of the galaxies we detected imply dust temperatures of greater than 20 K. As pointed out by Thronson *et al.* (1989, and references therein), the dust temperature inferred from the *IRAS* 60 μm and 100 μm bands may probe only a narrow range of physical conditions of the ISM in a galaxy and is probably not a reliable estimate of anything like a uniform dust temperature throughout the ISM. As a consistency check, we used the alternative ISM mass determination given by Jura (1986) based on a simple energy balance between blue and infrared light, wherein the dust optical depth in the blue is written as $\tau_B = \nu F_\nu (100\ \mu\text{m})/\nu F_\nu(B)$ (see § IV*b* for our estimates of $F_\nu[B]$). Although this method also depends on F_ν (100 μm), it is independent of assumed dust temperature. For all seven detected galaxies (including NGC 1275), both methods of mass determination yield agreement to within better than a factor of 2. In addition, we note that the ISM mass of NGC 1275 based on CO measurements (see § III*b*) also agrees well with both IR mass determinations, even though the 60 μm and 100 μm flux densities imply $T_d > 45$ K.

The possibility of a gas-to-dust ratio larger than 100 is a general concern for extragalactic observations and when indicated (e.g., Young *et al.* 1986; Thronson *et al.* 1989) is often discussed in the context of "corrections" or "allowances" which would bring the anomolous value in line with the canonical value. Young *et al.* suggest that only a fraction of the total dust in galaxies showing anomolous gas-to-dust ratios is warm enough to be detected by *IRAS*. This explanation is essentially equivalent to the argument that dust temperatures derived from F_ν (100 μm)/F_ν (60 μm) represent a restricted range of physical conditions of the ISM. The agreement between the IR and CO mass determinations for NGC 1275 noted above provides some support for the suggestion of Young *et al.* Again, the dependence of derived dust mass on the Planck function makes it sensitive to dust temperature; a relatively small uncertainty in temperature translates into a large change in derived mass, and hence gas-to-dust ratio. Because we do not have any independent information regarding the gas-to-dust ratios in the galaxies we studied, and given the somewhat tentative nature of the evidence for instances of high gas-to-dust ratios, adoption of the canonical value here seems reasonable. It should be kept in mind, however, that larger values are certainly possible, with the result that our derived masses would scale up accordingly.

b) CO

No CO was detected in any of the sources observed. The data for NGC 1275 were among those lost to the calibration software problem mentioned in the preceding section; CO emission from this galaxy was subsequently discovered by Lazareff *et al.* (1989). Upper limits to the CO luminosity and to the total mass of molecular gas in each galaxy have been determined on the basis of the assumed proportionality of integrated CO line intensity and H_2 column density, N_{H_2}. Numerically, $L_{CO} = I_{CO} \times (\pi/4)\, d_b^2$, where I_{CO} ($\equiv \int_{\text{line}} T\, dv$) is the integrated line temperature in units of K-km s^{-1} and d_b is the diameter of the telescope beam in kpc at the source distance. For comparison with most other extragalactic CO observations, the proportionality factor of Sanders *et al.* (1986) has been used. The mass of molecular hydrogen in units of $M_\odot$ is then given by $M_{CO} = 5.82 \times 10^6 L_{CO}$.

TABLE 3

CO Results[a]

Cluster	I_{CO} (K-km s^{-1})	L_{CO} (K-km s^{-1} kpc^2)	M_{CO} ($10^{10} M_\odot$)
A262	1.24	663	0.39
A496	0.81	1839	1.08
A978	1.27	7392	4.20
A1126	0.65	9228	5.40
A1185	0.83	2067	1.20
A1795	0.57	4686	2.73
A1983	1.00	4143	2.40
A2052	1.78	4452	2.58
A2199	1.49	3060	1.77
A2319	0.56	3231	1.89
2A 0335+096	0.59	1470	0.87

[a] All values are 3 σ upper limits.

Table 3 summarizes our results for the CO observations. The (3 σ) mass and luminosity upper limits derived are for a 100 channel bandpass ($\sim$530 km s^{-1}) centered on the redshifted CO frequency of the target galaxy; the rms noise was determined from 2 × 78 baseline channels located on either side of the central bandpass. Our values are consistent with the observational results of Bregman and Hogg (1988) for the dominant galaxies in A1126, A2199, and 2A 0335+096. The mass of NGC 1275 given in Table 3 is from Lazareff *et al.*, scaled to $H_0 = 50$ km s^{-1} Mpc^{-1}.

The assumption that the Galactic value of the I_{CO}-N_{H_2} conversion factor can be used for external galaxies is always somewhat arbitrary and, in some cases, probably incorrect. In the LMC, for example, Cohen *et al.* (1988) find that in order for molecular cloud masses determined using I_{CO} to agree with those derived by assuming the clouds to be in virial equilibrium, the conversion factor must be $\sim$6 times the Galactic value, or scale roughly with the inverse of the metalicity. (Good agreement between these two independent methods of mass determination is found for Galactic molecular clouds.) Iron line measurements of the hot intracluster medium in several clusters, however, indicate that abundances of about half solar are typical (e.g., Mushotzky *et al.* 1984; Ulmer *et al.* 1987). Because the intracluster medium must be the source of a cooling flow, adoption of the Galactic conversion factor seems reasonably well justified for our study. Also, as we noted above, M_{CO} derived by Lazareff *et al.* for NGC 1275 is in good relative agreement with its mass determined from the *IRAS* 100 μm flux density.

c) CO-*IR* Comparison

The CO luminosity upper limits are plotted against the IR luminosities (detections and upper limits) in Figure 1. Because our results provide mostly upper limits, it is not possible to infer how (or if) CO and IR luminosities correlate for the

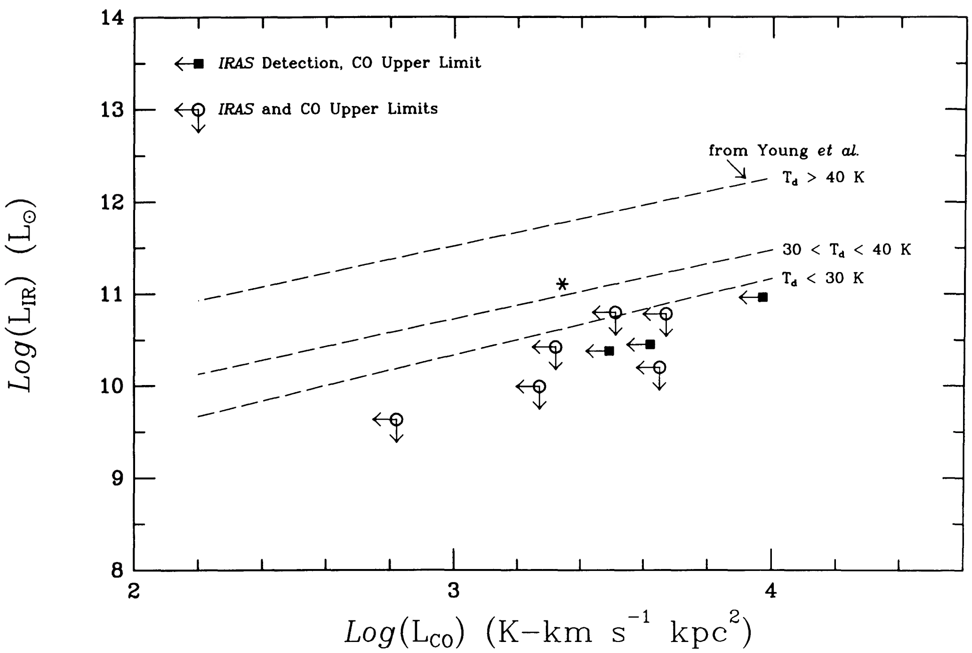

FIG. 1.—Luminosity comparison. The logarithms of L_{CO} and L_{IR} are plotted against each other for cluster-dominant galaxies. The parent clusters are A262, A426, A496, A978, A1126, A1185, A1795, A1983, A2052, A2199, and A2319. All L_{CO} values are 3 σ upper limits; downward arrows indicate 3 σ L_{IR} upper limits. The dashed lines show the L_{CO}-L_{IR} relation determined by Young *et al.* (1986) for spirals. The asterisk is NGC 1275 (in A426); L_{CO} is from Lazareff *et al.* (1989), scaled to $H_0 = 50$ km s^{-1} Mpc^{-1}.

cluster-dominant galaxies in our sample. If we assume that the infrared emission is tied (at least in part) to star formation, we can, however, get some indication of how these galaxies compare with spirals. The dashed lines in Figure 1 show the empirical L_{IR}-L_{CO} relation derived by Young *et al.* (1986), in three ranges of dust temperature, for spiral galaxies. The results for spirals are explained quite plausibly in terms of a correlation between molecular gas content and star formation, with dust temperature indicating the efficiency of star formation. Evidently, the CO luminosities (and presumably the molecular gas masses) of the galaxies we observed would in many cases have to be substantially lower than our upper limits in order for these galaxies to follow the same general trend found for spirals. This possibility would be consistent with the results of a recent study of S0 and Sa galaxies by Thronson *et al.* (1989). They concluded that while the star formation rates are lower in early-type disk galaxies than in later-type spirals, the formation rates per unit gas mass are similar in both types, assuming a normal initial mass function. Thus, if star formation is proceeding in the galaxies we observed according to a normal initial mass function, then it is apparently doing so at a fairly low rate. This interpretation must be reconciled with the continuous influx of available star-forming gas if a cooling flow is believed to be present. Alternatively, star formation rates and/or the initial mass function may be different in cooling flows than in spirals. The implications of our results are discussed further in the next section.

In addition to the galaxies shown in Figure 1 for which both CO and *IRAS* data were obtained, three galaxies were detected by *IRAS* but not observed in CO, and two were observed in CO, but either not observed by *IRAS* or no co-added data were obtained. The L_{IR}-L_{CO} relation of Young *et al.* has been used in these cases to predict the luminosity in the unobserved wave band based on the luminosity in the observed wave band. These five galaxies are shown in Figure 2. The predicted luminosities may be used to provide required sensitivity estimates for future observations.

IV. DISCUSSION

a) Detection Statistics

All of the galaxies in our sample detected by *IRAS* are in clusters reported to have X-ray evidence for cooling flows, raising the possibility of a correlation between the presence of cooling flows and the *IRAS* detection rate. To address this question without regard to any particular mechanism that might be responsible for such a correlation, we simply estimate the *a priori* probability of obtaining our results in the absence of any correlation. That is, we want the probability that x distinct objects selected at random from a total set of m are drawn from a predetermined subset of n of these (m total) objects. For very small values of this probability, the actual occurrence of such a selection of x from the n objects indicates that the subset n likely differs in some way from the other $(m - n)$ objects, assuming there are no biases in the initial selection of the total sample. This probability is given by the ratio of the number of unique ways to select x objects from n to the number of unique ways to select x from the total m:

$$\binom{n}{x} \bigg/ \binom{m}{x} .$$

In our case $m = 37$ is the total number of clusters for which we have *IRAS* data, $n = 20$ is the subset of those reported to have cooling flows, and x is the number detected. We consider a range in x, because our seven detections are not all of the same quality. Taking $x = 3$, 6, and 7 (see § III*a*), we obtain that the probability that the *IRAS* detection rate is uncorrelated

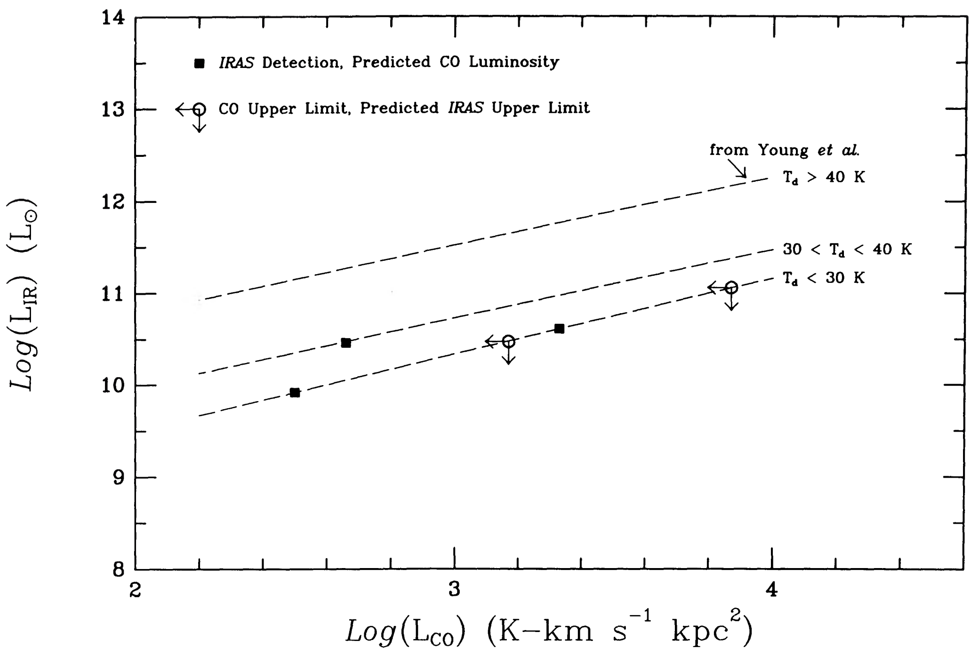

FIG. 2.—Predicted luminosities. Same as Fig. 1 except that for the galaxies shown here, only CO data or only *IRAS* data (for detections only), but not both, were obtained. The parent clusters are: A978 and 2A 0335+096 (CO data only; *open circles*); A400, A576, and A2063 (*IRAS* detections, no CO data; *filled squares*). The L_{CO}-L_{IR} relation determined by Young *et al.* (*dashed lines*) for spirals was used to predict L_{IR} (upper limits) based on values of L_{CO} derived from observations, and L_{CO} based on derived values of L_{IR} for the *IRAS* detections. All upper limits are 3 σ.

with the existence of cooling flows is 0.15, 0.02, and 0.01, respectively. Assigning greatest significance to our three best detections, it is clear that a strong argument for a correlation cannot be made. Even if all detections are considered to be equally reliable, the effect is only at the $\sim$99% confidence level, and a correlation is still not convincing.

Another indication of a correlation appears in a plot of L_{IR} versus reported mass-flow rate, as displayed in Figure 3. The blackened boxes show the six new detections, the asterisk shows NGC 1275, and the triangles show the upper limits to L_{IR} of the 13 remaining cooling-flow clusters. Note that both the derived L_{IR} and $\dot{M}$ scale with distance-squared. The dashed line shows a least-squares fit to the detections. Although the correlation coefficient of the fit is 0.87, five of the upper limits are inconsistent with the fit (below the line). To evaluate the scatter of the upper limits about the fit, we assume the upper

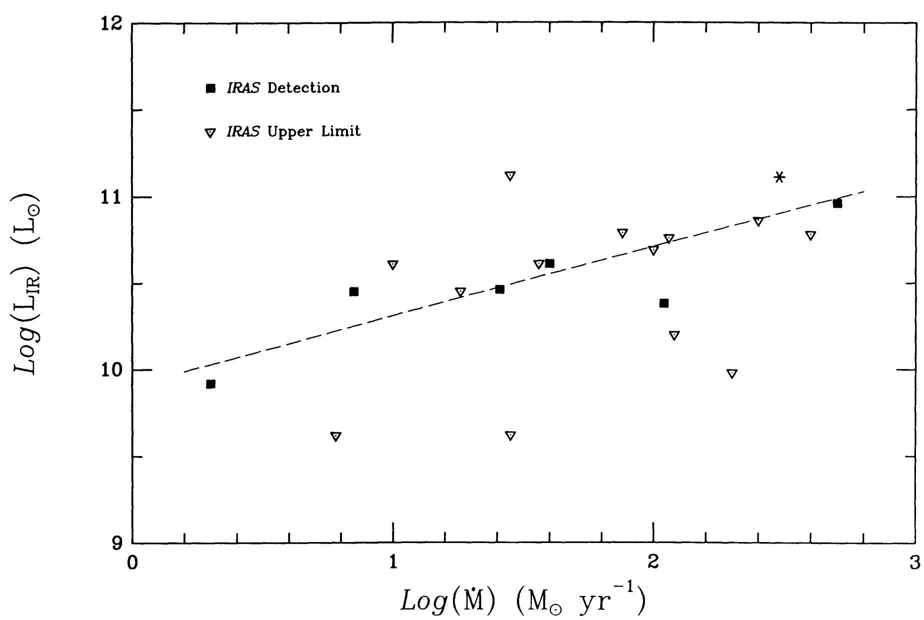

FIG. 3.—L_{IR} vs. flow rate. The logarithms of the mass-flow rates taken from the literature are plotted against the logarithms of L_{IR} (*filled squares*) or 3 σ upper limits to L_{IR} (*open triangles*). The asterisk is NGC 1275 (in A426). The dashed line is a least-squares fit to the detections. Although the fit is suggestive of a correlation, five of the upper limits are inconsistent with the fit, and we caution against using it to infer a physical relation between flow rate and L_{IR}.

limits represent the true infrared luminosities of the clusters and recalculate the fit including these points. In this case the correlation vanishes (the correlation coefficient of the new fit becomes 0.52). We conclude that the evidence does not bear a strong case for a correlation between L_{IR} and reported mass-flow rate.

Most of the galaxies in our sample simply do not have detectable amounts of cold gas or dust, at least at infrared or CO wavelengths. In this sense, the "control" sample, i.e., the subset of galaxies in clusters with long cooling times ($\gtrsim H_0^{-1}$), does not provide any strongly distinguishing information about the possible influence of cooling flows on the interstellar media of cluster-dominant galaxies. However, with the assumption that cooling flows exist, the lack of detections among those galaxies in the flows does have some implications for the rates and efficiencies of star formation fed by them. We focus on this question below. Although not directly related to cooling flows, we also give brief consideration to the comparative IR properties of cluster-dominant and elliptical galaxies.

b) *How Much Gas?*

We use a simple formalism to estimate the amount of cold interstellar gas that we might expect from a cooling flow at the present time, t_0. The mass of the ISM is denoted by $U(t)$ at time t, having an initial value of U_i. Mass from the cooling flow is taken to be the source of the ISM, and stellar mass, denoted by $S(t)$, is taken to be the sink. In terms of rates:

$$\frac{dU}{dt} \equiv \text{growth rate of the ISM} ,$$

$$\frac{dS}{dt} \equiv \eta \frac{U}{\tau} = \text{star formation rate} ,$$

$$\dot{M} \equiv \text{mass-flow rate} = \text{constant} ,$$

where τ is the lifetime of the ISM against star formation, η (≤ 1) is the star formation efficiency, and all masses are in units of $M_\odot$. Then,

$$\frac{dU}{dt} = -\eta \frac{U}{\tau} + \dot{M} .$$

Mass ejection from stars has been ignored because it is probably much smaller than the contribution from $\dot{M}$.

If τ is taken to be on the order of the free-fall time ($\ll t_0$), then η introduces processes which inhibit gravitational collapse and/or star formation on a local scale, such as magnetic fields or energetic disruption of star-forming regions by massive stars. For a discussion of star formation on a global scale, it is convenient to regard the quantity τ/η as an effective lifetime against star formation. Because both η and τ may vary with time, we use $\langle \eta/\tau \rangle = t^{-1} \int_0^t [\eta(t')/\tau(t')]dt'$, which allows the simplification

$$U(t = t_0) \approx U_i \exp\left(-\left\langle \frac{\eta}{\tau} \right\rangle t_0\right) + \dot{M}\left\langle \frac{\eta}{\tau} \right\rangle^{-1} \approx \dot{M}\left\langle \frac{\eta}{\tau} \right\rangle^{-1} .$$

Therefore, after some time t which exceeds $\langle \eta/\tau \rangle^{-1}$, we expect the reservoir to achieve an approximately constant size that depends on $\dot{M}$ and the time-averaged effective lifetime against star formation. In this picture, new stars are formed as rapidly as mass is added by the flow. Although this seems to imply 100% efficient star formation, the level at which the reservoir reaches a steady state does depend on η, which we have absorbed into the effective lifetime against star formation.

Figure 4 shows cooling mass-flow rates taken from the literature, plotted against the ISM masses or mass upper limits we derived from the *IRAS* detections and CO upper limits. There does not appear to be any correlation. (As with L_{IR}, both the derived M and $\dot{M}$ scale with distance-squared.) Taken at face value, this lack of correlation casts doubts on the existence of cooling flows, or at least suggests that the mass-flow rates may

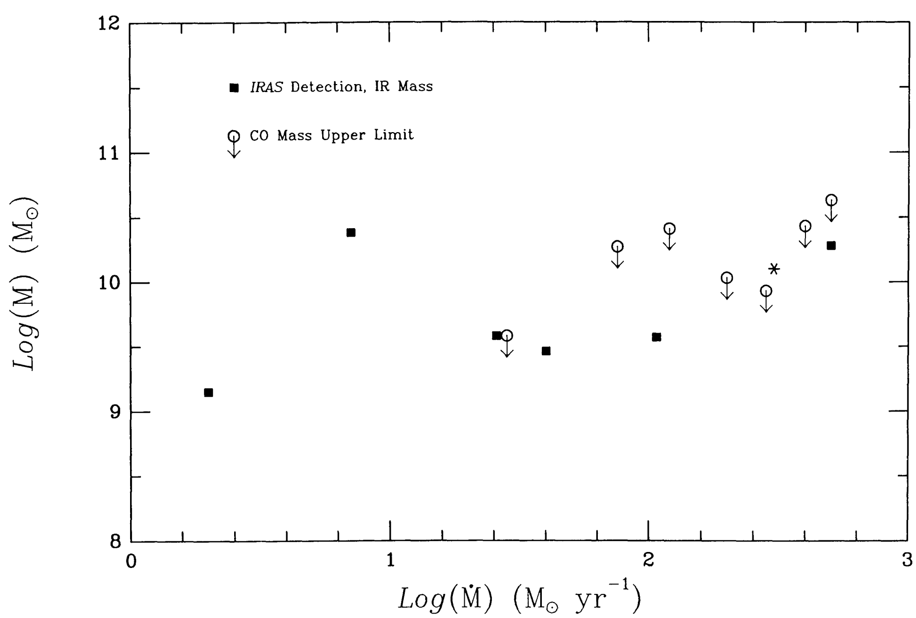

FIG. 4.—Mass vs. flow rate. The logarithms of the mass-flow rates taken from the literature are plotted against the logarithms of the IR-derived masses (*filled squares*) or 3 σ CO mass upper limits (*open circles*). Only galaxies detected by *IRAS* and/or observed for CO emission are shown. The asterisk is NGC 1275 (in A426); M_{CO} is from Lazareff *et al.* (1989), scaled to $H_0 = 50$ km s^{-1} Mpc^{-1}.

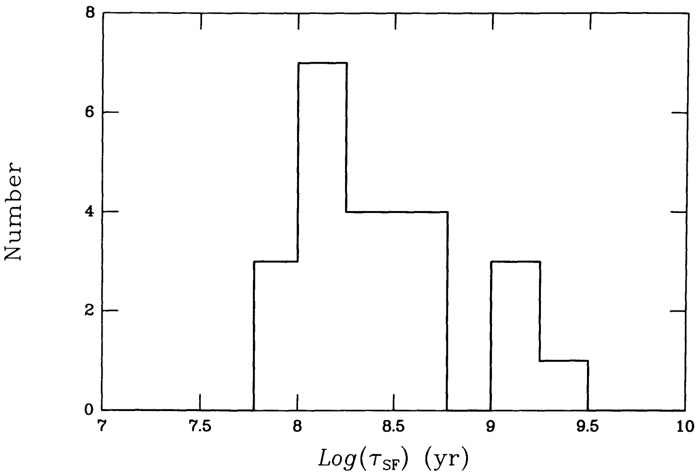

FIG. 5.—Star formation lifetime. The distribution of τ_{SF}, the time-averaged effective lifetime of the ISM against star formation, is shown. $\tau_{SF} \equiv 2M/\dot{M}$, where M is, in order of precedence, M_{IR} if the source was detected by *IRAS*, the upper limit to M_{CO} if the source was observed for CO emission, or the upper limit to M_{IR}. Most values of τ_{SF} are 3 σ upper limits.

have been overestimated. Alternatively, the failure to detect CO and IR emission from most of the galaxies in our sample could indicate that star formation rates are quite high, and that the reservoir of star-forming gas is therefore relatively small. This possibility can be evaluated by assuming cooling flows exist, then deriving $\langle \eta/\tau \rangle^{-1}$.

We redefine the quantity $\langle \eta/\tau \rangle^{-1}$ as $\tau_{SF} \equiv 2M/\dot{M}$, where the factor of 2 is assumed to account roughly for the fraction of the cold ISM detected: only half the ISM in the form of H_2 in the case where M is derived from the CO upper limits; or only half the neutral gas being warm enough to be detected by *IRAS* at 100 μm (see Jura 1986) in the case where M is derived from the *IRAS* 100 μm flux density. Figure 5 shows the distribution of τ_{SF}. The mean value is $\sim 10^8$ yr, fairly short considering that each τ_{SF} represents an average over an entire galaxy and over time. In fact, τ_{SF} may be even shorter since Figure 5 contains mostly upper limits. By contrast, an estimate of the time-averaged lifetime against star formation for the Galaxy is $\tau_{SF,Gal} \gtrsim 10^9$ yr (Reeves 1975). If in analogy to our discussion above, $\tau_{SF,Gal} \sim \langle \tau_{Gal}/\eta_{Gal} \rangle$, where τ_{Gal}^{-1} is an "unimpeded" rate and η_{Gal} is the Galactic efficiency factor, and if $\tau_{Gal} \sim \tau$ in cooling flows, then η must be relatively large in cooling flows. (Conversely, η_{Gal} must be relatively small, which is in fact the case for star formation in Galactic giant molecular clouds [Myers *et al.* 1986; Grabelsky 1985]).

An interesting implication that follows from this discussion is that star formation in cooling flows and in spiral galaxies may be different. In spiral galaxies, high star formation efficiencies have been associated with high dust temperatures, high infrared luminosities, and large ratios of L_{IR}/L_{CO} (Young *et al.* 1986). Our results indicate that if cooling flows with $\dot{M} \sim 100\ M_\odot\ \mathrm{yr}^{-1}$ exist, then star formation fed by them is highly efficient. At the same time, however, the infrared luminosities (detections and upper limits) of the galaxies we observed are relatively low, a property which in spiral galaxies seems to indicate fairly low star formation rates. If the formation of massive stars is somehow suppressed in cooling flows, vigorous low-mass star formation might still proceed without significantly heating the interstellar gas and dust, thereby maintaining fairly low infrared luminosities. This would be consistent with cooling flow models in which star formation is characterized by a truncated initial mass function (Sarazin and O'Connell 1983; O'Connell and McNamara 1989). Of course, if cooling flows are not actually present, or if mass-flow rates have been greatly overestimated, then the relatively small ISM masses and low infrared luminosities we find would be consistent with the results for spirals, without invoking different modes of star formation.

c) Far-IR Comparison of Cluster-dominant and Elliptical Galaxies

Recently, Jura *et al.* (1987) found that *IRAS* detected up to one-third of the roughly 60 brightest ($B_T^0 \leq 12.0$ mag) elliptical galaxies in the Revised Shapely-Ames Catalog (Sandage and Tammann 1981). Using our results, we can make a rough comparison of the FIR properties of cluster-dominant and elliptical galaxies. Our discussion is limited to the six galaxies from our sample detected by *IRAS*; NGC 1275 (classified in the Shapley-Ames Catalog as an Ep galaxy) is omitted because it is already included in the study of Jura *et al.*

Table 4 lists the relevant magnitudes and flux densities. The redshift-corrected V magnitudes are from Hoessel, Gunn, and Thuan (1981) for A400, A1126, A1983, A2063, and A2199, and from Peterson (1970) for A576. The B magnitudes were inferred simply by adding 0.9 to the V magnitudes (Allen 1973). The uncertainty in this procedure is probably large enough to ignore the small redshift corrections, so we have done so. We converted the B magnitudes to flux densities using $F_\nu(B) = 4.44 \times 10^{[6-(B/2.5)]}$ mJy (Johnson 1966), scaling the result by ~ 4. The scale factor adjusts approximately for the portion of the galaxy beyond the aperture used in measuring V: Hoessel *et al.* and Peterson used metric aperture radii of 16 kpc and 17 kpc ($H_0 = 60$ km s^{-1} Mpc^{-1}), respectively, compared with a radius of $\gtrsim 30$ kpc for a typical cD envelope (e.g., Morgan and Lesh 1965).

For ellipticals, Jura *et al.* find that the *IRAS* 12 μm flux densities correlate reasonably well with the flux densities at B, the interpretation being that stars are responsible for the emission in both wave bands. A simple "eyeball" fit to their data gives F_ν (12 μm) $\sim 10[F_\nu(B)]^{1/2}$ (in units of mJy). By contrast, there does not appear to be any correlation between $F_\nu(B)$ and the 100 μm flux density in ellipticals, supporting the hypothesis that the 100 μm emission arises from interstellar dust and is

TABLE 4

DERIVED[a] B MAGNITUDES AND FLUXES

Cluster	V[b]	B	$F_\nu(B)$ (mJy)
A400	13.16	14.06	42.2
A576	14.37	15.27	13.8
A1126	14.97	15.87	8.0
A1983	14.84	15.74	8.8
A2063	13.72	14.62	25.2
A2199	12.74	13.64	62.0

[a] See § IV*b*.

[b] References for V magnitudes: A400, A1126, A1983, A2063, and A2199 are from Hoessel, Gunn, and Thuan 1980; A576 is from Peterson 1970. These correspond to integrated magnitudes within metric radii of ~ 16 kpc (scaled to $H_0 = 60$ km s^{-1} Mpc^{-1}).

not directly tied to stars. Of the six galaxies detected at 60 μm and 100 μm, none were detected at 12 μm (excluding NGC 1275), so we are restricted to checking the consistency of our results with those for ellipticals.

Extrapolating the F_ν (12 μm)-$F_\nu(B)$ relation for ellipticals to our derived B flux densities, we would predict 12 μm fluxes below the *IRAS* sensitivity and consistent with our upper limits. We cannot rule out the possibility that the galaxies we observed are overluminous in B with respect to 12 μm, but there is no *a priori* reason for expecting this to be the case. The flux density ratios F_ν (100 μm)/$F_\nu(B)$ for the cluster-dominant galaxies are in the same range as that found for ellipticals. Similarly, there is no apparent correlation between the flux densities in these two wave bands for the cluster-dominant galaxies detected. As with ellipticals, then, we expect that the 100 μm emission is a tracer of interstellar dust.

We have already assumed similar FIR emission properties for cluster-dominant and elliptical galaxies when we computed ISM masses based on the *IRAS* 100 μm flux densities. The resulting masses ranged roughly from 10^9 to 10^{10} $M_\odot$ (see § III). Jura *et al.* find a range of 10^7–10^8 $M_\odot$ for ellipticals, also from the 100 μm flux densities. The implied ratios of ISM masses correspond fairly well with ratios of total mass for typical normal elliptical and cD galaxies (e.g., Morgan and Lesh 1965; Sarazin 1986 and references therein). On the basis of this limited comparison of infrared properties, cluster-dominant galaxies appear to be "scaled-up" ellipticals.

V. SUMMARY AND CONCLUSIONS

We have used the *IRAS* survey to search for cold interstellar gas in 37 galaxies in the cores of clusters with and without reported cooling flows, and observed 11 galaxies for CO emission. Six new *IRAS* sources have been detected in addition to one previously detected galaxy (NGC 1275), but no CO emission was observed. Our results do not provide a clear-cut answer to the question[4] "do cooling flows *really* exist?" Although all the detected galaxies are in clusters reported to have cooling flows, the detections are too few to distinguish, in general, clusters with evidence for cooling flows from those without, on the basis of their FIR properties. Furthermore, the evidence for a trend connecting L_{IR} with estimated mass-flow rates is weak.

If cooling flows do exist, however, then it would appear that star formation fed by them must be rapid and efficient in order to render the ISM undetectable. Rapid and efficient star formation in spirals has been linked to high infrared luminosities, yet the galaxies in our sample generally have relatively low IR luminosities. This may suggest that massive stars which heat the gas and dust in spirals do not form abundantly (if at all) in cooling flows, a scenario consistent with some cooling flow theories which predict a truncated initial mass function (Sarazin and O'Connell 1983; O'Connell and McNamara 1989). Alternatively, there may be very little dust in the ISM which results from accretion of a cooling flow, also consistent with some theoretical predictions (Fabian, Nulsen, and Canizares 1982). In any case, the ISM and stars formed by cooling flows remain elusive.

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[4] See "What Your Colleagues Want To Know," in *Radio Continuum Processes in Clusters of Galaxies*, 1986, ed. C. O'Dea and J. Uson, p. 347.

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D. A. Grabelsky and M. P. Ulmer: Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208