

## High-luminosity *IRAS* galaxies – I. The proportion of *IRAS* galaxies in interacting systems

A. Lawrence, M. Rowan-Robinson and K. Leech

*Astronomy Unit, School of Mathematical Sciences, Queen Mary College, Mile End Road, London E1 4NS*

D. H. P. Jones and J. V. Wall *Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex BN27 1RP*

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**Summary.** We report CCD imaging of a complete sample of 60 high-luminosity *IRAS* galaxies (selected as a subset of the redshift survey by Lawrence *et al.*), and of a control sample of 87 optically selected galaxies from the Durham redshift survey. The galaxies have been grouped in seven classes depending on the presence or absence of faint or bright, nearby or distant, companions, and signs of interaction or mergers such as tidal arms or disturbed structure. We find that  $18 \pm 5$  per cent of optically selected galaxies are in interacting or merging systems. The proportion of low-luminosity ( $< 10^{11} L_{\odot}$ ) *IRAS* galaxies which are interacting or merging,  $11 \pm 8$  per cent (2/19), is consistent with this.

At high luminosities ( $> 10^{11} L_{\odot}$ ) the proportion is  $46 \pm 12$  per cent (19/41). The *excess* of interacting pairs over those which we would expect to find by chance is therefore about 30 per cent. Many of the pairs are unresolved by the *IRAS* beam, but we demonstrate that this cannot explain the enhanced fraction of pairs. These results indicate that galaxy interaction is a common causal factor in luminous IR activity, but also that it is far from being the ubiquitous factor suggested in several recent reports.

### 1 Introduction

Much evidence has accumulated that interactions between galaxies play an important part in causing energetic activity. This evidence has been of two types: (1) A few studies have examined galaxies selected to be active and found that they are more likely to be interacting, or otherwise peculiar, than normal galaxies (e.g. Dahari 1984 for Seyfert galaxies; Stauffer 1982 for LINERs; Heckman *et al.* 1986 for powerful radio galaxies; Condon *et al.* 1982 for radio sources in spiral galaxies; Sanders *et al.* 1988a for ‘warm’ IR-selected Seyfert galaxies). (2) More frequently, some indicator of the level of activity has been measured for a sample of

morphologically normal galaxies and for a sample of interacting galaxies, the latter usually drawn either from the Arp Atlas (Arp 1966) or from the *Catalogue of Pairs of Galaxies* (Karachentsev 1972). Such work has consistently shown that interacting systems are systematically more 'active' in some sense (e.g. Stocke 1978; Hummel 1981 for radio emission; Larson & Tinsley 1978 for *UBV* excess; Joseph *et al.* 1984a and Joseph & Wright 1985 for near-IR excess; Lonsdale, Persson & Matthews 1984 and Cutri & McAlary 1985 for mid-IR excess; Kennicutt & Keel 1984 and Keel *et al.* 1985 for emission-line strength).

Studies of both types have been concerned with disparate kinds of activity – radio emission, Seyfert activity, LINER activity and starburst activity. Some of the evidence seems contradictory – for example Stauffer (1982) finds that LINER-type nuclei occur preferentially in groups and pairs of galaxies, but Keel *et al.* (1985) find that, in close pairs, Seyfert and starburst activity is enhanced at the expense of LINER-type activity. Also it should be noted that studies of Type (1) indicate that, while interaction has a clear statistical link with activity, the *majority* of active galaxies are *not* obviously interacting.

Renewed interest in this question has come with the discovery that many IR-luminous galaxies in the *IRAS* survey are interacting systems. This began, before publication of the *Point Source Catalog* (PSC), with the discovery that two peculiar galaxies, Arp 220 and NGC 6240, are extremely luminous in the IR, with  $L_{\text{FIR}} > 10^{12} L_{\odot}$  (Soifer *et al.* 1984b; Wright, Joseph & Meikle 1984; Joseph, Wright & Wade 1984b). For galaxies in the 'minisurvey', Soifer *et al.* (1984a) found 12–20 per cent to have close companions. For new identifications of a complete flux-limited sample from the PSC, Lawrence *et al.* (1986) found 24 per cent to have companions of some kind. In the last two studies the proportion of close pairs is considerable but very far from a majority. Since it is also clear that the bulk of galaxy identifications in the PSC as a whole are normal spiral galaxies (de Jong *et al.* 1984; Lawrence *et al.* 1986), it is of greater interest to consider the more luminous objects. Allen, Roche & Norris (1985), in a sample of 19 optically faint galaxies identified with *IRAS* sources, found that 68 per cent are disturbed, interacting or have close companions. Sanders *et al.* (1986), in the course of a CO study of 15 galaxies with  $L_{\text{FIR}} > 10^{11} L_{\odot}$ , noted that the majority, if not all, appeared to be strongly interacting systems. Armus, Heckman & Miley (1987) have obtained CCD images of 39 *IRAS* galaxies with warm 25–100  $\mu\text{m}$  colours and high infrared-to-optical ratios. For the 17 for which they have redshifts, they find far-infrared luminosities  $> 10^{11} L_{\odot}$ . They find that two-thirds of this sample have strange structures, compared with 14 per cent for an optically selected control sample of 28 galaxies. Telesco, Wolstencroft & Done (1988) have found that, among the interacting pairs of galaxies in the *Arp-Madore Catalogue of Southern Peculiar Galaxies and Associations*, the closer pairs have enhanced infrared emission. Most recently, Sanders *et al.* (1988b) have discussed deep CCD images of a statistically complete sample of ten galaxies with  $L(40\text{--}120 \mu\text{m}) > 10^{12} L_{\odot}$ , selected from the *Bright Galaxy Survey* of Soifer *et al.* (1987), flux-limited at  $S(60 \mu\text{m}) = 5.4 \text{ Jy}$ . They find that all ten show some kind of morphological peculiarity, and furthermore that nine out of ten are active galactic nuclei of some kind.

The study we present here concerns a large (60) statistically complete sample of IR-luminous galaxies, not biased towards warm colours. We examine both Sky Survey material and new CCD images. We have also studied a matched control sample of 87 optically selected galaxies, selected from the Durham redshift survey (Peterson *et al.* 1986). A companion paper (Leech *et al.*, 1989, Paper II) describes optical spectroscopy of the same sample.

## 2 Definition of samples

### 2.1 THE *IRAS* SAMPLE

This is based on the *IRAS* galaxy redshift survey by Lawrence *et al.* (1986). The 'main sample' of that paper was selected from the first version of the *IRAS Point Source Catalog*, and was

defined by: (i)  $b > 60^\circ$ ,  $0 < l < 110^\circ$ , (ii)  $S(60 \mu\text{m}) > 0.85 \text{ Jy}$ , (iii)  $\log[S(60)/S(25)] > -0.5$ , a condition which excludes the few bright stars found at  $60 \mu\text{m}$ . This produces a list of 237 *IRAS* sources, all of which are clearly identified with galaxies. At the time of writing, only one of these objects has no velocity available (13279 + 3401). When the observations described in this paper were undertaken, there were two other galaxies with no velocity available (14336 + 2456 and 13593 + 3107). These two galaxies were therefore not included in the sample selection described below. New velocities for all objects except 14336 + 2456 are given in Leech *et al.* (1988). As noted by Lawrence *et al.* (1986), the majority of these identifications are relatively normal spiral galaxies in terms of infrared luminosity. For the present study (and for the companion study described in Paper II) we wanted to define a subset that is dominated by relatively high-luminosity galaxies, and is also towards the higher end of the flux density distribution. This led to the following definition:

- (i) from the flux-limited sample by Lawrence *et al.* (1986),
- (ii)  $z > 0.01$  (so that a typical galaxy would fit entirely onto a CCD chip area),
- (iii) either  $S(60 \mu\text{m}) > 2 \text{ Jy}$ , or  $S(60 \mu\text{m}) > 1 \text{ Jy}$  and  $\log[L(60 \mu\text{m})/L_\odot] > 11.5$ .

Here  $cz$  includes a standard correction for rotation about the Galactic Centre of  $300 \sin(l) \cos(b) \text{ km s}^{-1}$ . Luminosities are  $\nu L_\nu$ , using  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega = 1$ , and K-corrected assuming a spectral index of  $-2$ . The conditions produce a sample of 60 *IRAS* sources, which are listed in Table 1a. The table also lists positions and fluxes from the PSC, optical synonyms, velocities, luminosities, and spectral types from Leech *et al.* (1988, 1989), and arcsecond positions of optical counterpart(s), measured with the RGO coradograph. The luminosity distribution of the sample is shown in Fig. 1, and compared with the luminosity distribution of IR-selected galaxies as a whole, and optically selected (Shapley-Ames) galaxies. As intended, the new sample efficiently selects the most-luminous IR galaxies, but still has a fair proportion of relatively normal galaxies [ $L(60 \mu\text{m}) = 10^{10} - 10^{11} L_\odot$ ] for comparison purposes.

## 2.2 THE CONTROL SAMPLE

This was selected from the Durham redshift survey (Peterson *et al.* 1986), excluding objects classified as ellipticals or lenticulars, and matched in redshift and magnitude distribution. First, the *IRAS* sample was grouped in bins of  $\log(\text{velocity})$  and estimated photographic magnitude (from the Palomar Observatory Sky Survey). A similar fraction of control galaxies were then picked in each bin, using the velocities and *B* magnitudes from Peterson *et al.* Because the *IRAS* luminosity function is so broad, there are, however, a small number of very nearby and very distant objects in the *IRAS* sample which are not matched in the control sample. The resulting control sample of 87 galaxies is listed in Table 1b. Amongst this control sample there are three *IRAS* PSC sources, one of which is coincident with a pair of galaxies, both of which are in the control sample (see notes to Table 1b). All three have *IRAS* luminosities in the high-luminosity category ( $> 10^{11} L_\odot$ ). Our basic results, summarized in Table 2, are given with and without these objects.

## 3 Observations, data reduction and classification

Imaging observations were made at the Observatorio del Roque de los Muchachos (La Palma) using the CCD system at the  $f/15$  Cassegrain focus on the 1-m Jacobus Kapteyn Telescope (JKT) in the week of 1986 April 10-17 and on the Isaac Newton Telescope (INT) on 1987 June 2-4. For the JKT observations the chip used was an RCA 53612, thinned and back-illuminated. Bias level is monitored via an overscanned strip. Flat fields were obtained by exposure on a blank field in twilight. All 60 sample objects were observed, using a Kitt Peak R

**Table 1a.** Properties of *IRAS* sample.

(1)RA	(2)DEC	(3)S60	(4)VEL(REF)	(5)L60	(6)OPTICAL SYNONYMS	(7)OPT.RA	(8)OPT.DEC(REF)	(9)INT.CLASS	(10)SP.CLASS	(11)comments
1259010	293458	651	7071(H)	11.32	N4922A+B	U8135	M5-31-99	ZG1259+29		
1259012	293456(D)	5*	LINER	(N of pair ;	VCV catalogue claims	Sy2)				
1259002	293436(D)		(S of pair)							
1300352	355614	277	11016(Q)	11.34	NEW					
1300356	355612(Q)	6	HII	(partial ring or detached arm,	no obvious companion)					
1308389	295038	219	7211(H)	10.87	N5004C	U8259	M5-31-150	ZG1308+29		
1308393	295408(D)	2	HII	(barred spiral, distant bt	comp=N5004A)					(position given by (D) for N5004 is clearly N5004A, not the IRAS source)
1311115	434808	303	17261(Q)	11.78	NEW					
1311118	434807(Q)	1	HII	(smooth, E ? faint distant	companion)					
1312401	245252	1735	3871(H)	11.22	M4-31-15	ZG1312+24				
1312396	245258(Q)	0	HII	(early spiral (can see arms	in B and V images))					
1318191	342349	1487	6943(H)	11.67	IC883	U8387	ZG1318+34	ARP193	IZW56	
1318172	342406(Q)	6*	HII	(merger - multiple nuclei,	jets)					
1323533	361132	443	5621(H)	10.95	N5149	U8444	M6-30-010	ZG1323+36		
1323535	361138(D)	0	HII	(isolated spiral)						
1325257	475438	181	18213(Q)	11.61	NEW					
1325261	475434(Q)	2*	HII	(smooth, E ? distant bright	and faint companions)					
1325234	475428(Q)		(bright companion)							
1332409	341759	276	7423(H)	10.99	U8561	M6-30-46	ZG1332+34			
1332417	341758(D)	1	HII	(late type spiral, distant	faint companion)					
1334125	393241	112	53921(Q)	12.41	NEW					
1334125	393247(Q)	0	Sy2	(compact, isolated)						( but v.ft images around, cluster ?)
1336141	483153	720	8353(H)	11.52	N5256	U8632	M8-25-31	ZG1336+48	MKN266	IZW6
1336152	483153(D)	5*	LINER/Sy2	(interacting pair, compact)						
1337365	283911	361	4886(H)	10.74	N5263	U8648	M5-32-58	ZG1337+28		
1337370	283908(D)	0	HII	(single spiral)						
1338464	233159	498	8172(Q)	11.33	M4-32-25	ZG1338+23				
1338464	233204(Q)	3	LINER	(brighter of two spirals,	no sign of disturbance)					
1338480	233148(Q)		(fainter companion to SE)							

Table 1a - continued.

(1)RA	(2)DEC	(3)S60	(4)VEL	(REF)	(5)L60	(6)OPTICAL	SYNONYMS	(7)OPT.RA	(8)OPT.DEC	(REF)	(9)INT.CLASS	(10)SP.CLASS	(11)comments
1338468	295144	144	23368	(Q)	11.74	NEW							
1338454	295151	(Q)	0	HII		(isolated, compact, smooth, elliptical ?)							
1340520	303519	228	10455	(H)	11.22	U8685 M5-32-74 ZG1340+30							
1340522	303516	(D)	0	HII		(isolated barred spiral)							
1344178	232119	171	42441	(Q)	12.37	U8706 ? NEW ?							
1344168	232054	(Q)	4*	HII		(SW of pair, has emission)							
1344182	232116	(Q)				(NE of pair, brighter but dull)							
1345478	351302	102	34876	(Q)	11.96	NEW							
1345448	351325	(Q)	3	HII		(nearby faint companion)							
1345449	351316	(Q)				(faint companion)							
1347016	353014	599	5108	(Q)	10.90	U8739 M6-30-90 ZG1347+35							
1347024	353016	(Q)	1	HII		(edge on spiral, bright HII regions)							(also 2 fainter galaxies)
1353153	251741	215	8790	(Q)	11.05	NEW							
1353157	251739	(Q)	2	HII		(correct ID is 1.5' SSE of interacting pair VV281)							
1353397	183658	216	14940	(H)	11.51	U8850 M3-36-5 ZG1353+18 MKN463							
1353397	183659	(Q)	6*	Sy2/HII		(two nuclei, E is Seyfert, W is HII)							(position is unresolved centroid from Sky Survey)
1353525	301942	200	9439	(Q)	11.06	U8856 ZG1354+30 M5-33-21							
1353529	301931	(Q)	5*	HII		(MCG5-33-22 one diam away, intervening material)							
1353544	292009	196	32789	(Q)	12.19	NEW							
1353542	292014	(Q)	6*	HII		(irregular, other ft images; merging cD in cluster ?)							
1356252	374139	709	3490	(H)	10.74	N5394 U8898 M6-31-33 ZG1356+37 ARP84 V048B							
1356252	374151	(D)	5	HII		(spiral N of brighter gal (N5395), tidal arms)							
1356253	374147	(G)				(brighter companion N5395)							
1356308	351950	294	10600	(Q)	11.33	M6-31-36							
1356312	351952	(Q)	5	HII		(near faint companion, elongated spiral arm)							
1356300	351936	(Q)				(faint companion)							
1357182	251734	127	19256	(Q)	11.51	NEW							
1357183	251737	(Q)	0	HII		(compact, single, but some v.ft images, cluster ?)							

Table 1a - continued.

(1)RA (2)DEC (3)S60 (4)VEL(REF) (5)L60 (6)OPTICAL SYNONYMS  
(7)OPT.RA (8)OPT.DEC(REF) (9)INT.CLASS (10)SP.CLASS (11)comments

1358555 430526 246 10031(Q) 11.20 M7-29-36  
1358553 430548(Q) 4\* HII/dull (Two galaxies, IRAS posn in middle ; N dull)  
1358561 430511(Q) (South galaxy HII)

1400239 324502 676 4348(H) 10.91 N5433 U8954 M6-31-50 ZG1400+32  
1400240 324458(D) 0 HII (isolated spiral)

1400489 281618 232 4790(Q) 10.52 U8961 M5-33-42  
1400484 281624(Q) 0 HII (isolated spiral)

1402368 305845 269 7770(Q) 11.02 M5-33-46 ZG1402+30  
1402348 305857(Q) 0 HII (isolated spiral)

1404385 340033 259 10691(Q) 11.28 M6-31-070 ZG1404+34  
1404388 340033(Q) 0 HII (single, compact)

1404508 152423 217 7420(H) 10.89 M3-36-49 ZG1404+15  
1404526 152414(Q) 0 HII (single, compact)

1405449 322703 150 25975(Q) 11.85 NEW  
1405453 322701(Q) 5 HII (interacting with compact companion)  
1405455 322702(Q) (compact companion)

1406043 291900 159 35046(Q) 12.16 NEW  
1406050 291858(Q) 6 HII (compact, asymmetric halo, plume, no obvious comp.)

1408166 134733 364 4948(Q) 10.76 ZG1408+13  
1408163 134736(Q) 0 Sy2 (isolated)

1409361 242813 150 18572(Q) 11.54 NEW  
1409361 242813(Q) 0 HII (single)

1412258 152245 205 4606(H) 10.44 N5522 U9116 M3-36-89 ZG1412+15  
1412263 152245(D) 0 HII (single spiral)

1414285 394916 238 7804(H) 10.97 N5541 U9139 M7-29-59 ZG1414+39  
1414291 394915(D) 5 HII (barred spiral, interacting with faint companion)

1415061 270517 285 10826(H) 11.34 U9141 M5-34-7 ZG1415+27 MKN673  
1415063 270518(Q) 6\* HII/HII (double nucleus ; position is centroid)  
1415040 270526(Q) (third galaxy in system)

Table 1a - continued.

(1)RA	(2)DEC	(3)S60	(4)VEL(REF)	(5)L60	(6)OPTICAL SYNONYMS
(7)OPT.RA	(8)OPT.DEC(REF)	(9)INT.CLASS	(10)SP.CLASS	(11)comments	
1415489	274148	230	20987(Q)	11.84	NEW
1415492	274149(Q)	5	HII		(interacting with faint companion)
1415488	274133(Q)				(faint companion)
1416304	251017	307	5659(Q)	10.77	U9165 ZG1416+25 M4-34-15
1416316	251009(Q)	2*	HII		(edge on spiral, distant companion)
1417538	492754	615	8144(Q)	11.41	ZG1417+49 MKN1490
1417537	492756(Q)	0	HII		(single, stellar nucleus)
1420160	261543	144	47397(Q)	12.40	NEW
1420167	261543(Q)	3	HII		(nearby fainter companion, not obviously interacting)
1420162	261545				(faint companion)
1420194	300558	102	34221(Q)	11.94	NEW
1420188	300601(Q)	1	Sy2		(compact, faint distant companion)
1420183	300543				(faint companion)
1422070	245024	477	5143(H)	10.91	N5610 U9230 M4-34-25 ZG1422+24
1422073	245023(D)	0	HII		(single barred spiral)
1422494	135806	225	5590(Q)	10.66	U9239 ZG1422+13
1422492	135810(Q)	0	HII		(single edge on spiral)
1422583	142455	181	17943(Q)	11.60	NEW
1422581	142459(Q)	5*	HII		(NW of close pair, plume of faint material to south)
1422586	142447(Q)				(NE of pair)
1427108	420309	224	5518(Q)	10.62	U9307 M7-30-16 ZG1427+42
1427107	420308(Q)	0	HII		(single spiral)
1428002	312617	1078	3599(H)	10.95	N5653 U9318 M5-34-58 ZG1427+31
1428012	312611(D)	0	HII		(single spiral, bright HII regions, stellar nucleus)
1428209	353229	269	3292(H)	10.27	N5656 U9332 M6-32-53 ZG1428+35
1428201	353228(D)	0	HII		(single spiral)
1429363	220931	224	13332(Q)	11.42	ZG1429+22
1429371	220929(Q)	5	HII		(faint companion, joining bridge, strong nucleus)
1433142	352007	284	8767(Q)	11.14	M6-32-70
1433140	352013(Q)	0	HII		(single spiral)

Table 1a - continued.

(1)RA (2)DEC (3)S60 (4)VEL(REF) (5)L60 (6)OPTICAL SYNONYMS  
(7)OPT. RA (8)OPT.DEC(REF) (9)INT.CLASS (10)SP.CLASS (11)comments

1435400 304157 235 10491(Q) 11.22 U9425 M5-34-83 ZG1435+30  
 1435417 304156(Q) 5\* HII/HII (N of close pair, tidal arms)  
 1435422 304144(Q) (S of pair)

1440330 263415 116 32514(Q) 11.95 NEW  
 1440327 263414(Q) 0 HII (several very faint galaxies around, cluster ?)

1442149 164409 201 6636(Q) 10.75 NEW  
 1442159 164409(Q) 0 HII (single, S0 or E ?)

1443267 385920 243 9865(Q) 11.18 N5755 U9507 M7-30-63 ZG1443+38  
 1443262 385923(Q) 5\* HII (disturbed, also large spiral several diameters away  
 1443250 385926(Q) (NW blob)  
 1443250 385926(Q) (SW blob)

1445569 174530 101 46156(Q) 11.52 NEW  
 1445564 174533(Q) 0 HII (single)

1447108 233318 173 26183(Q) 11.92 NEW  
 1447111 233319(Q) 5\* HII/HII (W of close pair, tidal arm)  
 1447118 233322(Q) (E of pair)

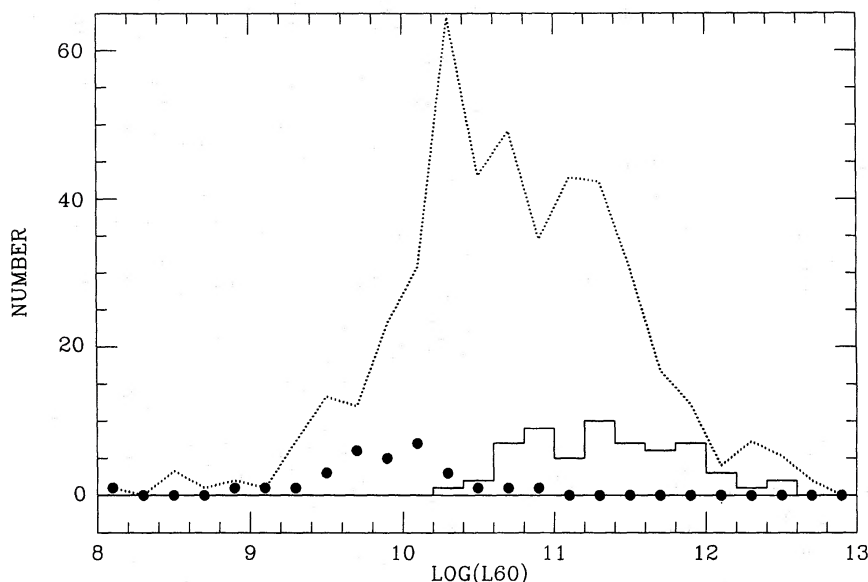
1454479 244857 637 10247(H) 11.64 U9618 M4-35-18,19 ARP302 V340  
 1454486 244902(D) 5\* HII/HII (N of pair of spirals, faint common envelope)  
 1454481 244821(D) (S of pair)

1457332 325651 120 34198(Q) 12.01 NEW  
 1457331 325652(Q) 0 HII (isolated, smooth, elliptical ?)

1501491 241753 297 20860(Q) 11.95 NEW  
 1501486 241757(Q) 5 HII (spiral int. with faint companion)  
 1501477 241757(Q) (faint companion)

Notes: (1, 2) *IRAS* RA/Dec (1950.0), from PSC; (3) 60  $\mu\text{m}$  flux in centi-Jy; (4) Galactocentric velocity,  $\text{km s}^{-1}$ ; Q = Leech *et al.* 1988a, H = private compilation of J. Huchra; (5) log of 60  $\mu\text{m}$  luminosity, as described in text; (6) Abbreviations used for optical synonyms: N = NGC, U = UGC, M = MCG, ZG = Zwicky Catalogue, V = Vorontsov-Velyaminov; (7, 8) RA/Dec (1950.0) of optical counterpart(s); Q = this paper ( $\pm 1''$ ); D = Dressel & Condon 1976 ( $\pm 5''$ ), G = Gallouet *et al.* 1975 ( $\pm 5''$ ); (9) interaction class, as described in text; \* means more than one galaxy possible contributing to *IRAS* source; (10) optical spectroscopic classification, from Leech *et al.* 1988b; (11) subjective descriptive comments.

filter, with a 5–10 min exposure, in largely transparent but non-photometric conditions. A subset of 15 were also observed photometrically at *B*, *V* and *R* during two nights, but these data are not considered here. Data frames were reduced in the usual manner by subtracting a bias frame and dividing by a flat field, and were subsequently examined on an image processing



**Figure 1.** Distribution of 60- $\mu\text{m}$  luminosities for *IRAS* galaxies in 844 deg<sup>2</sup> at the north galactic pole. Dotted line = all galaxies with  $S(60\ \mu\text{m}) > 0.5\ \text{Jy}$ . This was constructed from the 'main' and 'supplementary' samples of Lawrence *et al.* (1986), assuming that the latter, taken from a third of the area, is representative of the whole area. Filled circles = Shapley-Ames galaxies in the same area. (c) Histogram = the new 'high-luminosity' sample of the present paper.

monitor, all using the ASPIC software of the UK STARLINK network. Seeing was modest by La Palma standards, 1–2 arcsec. Tracking and mirror stability of the JKT at this time was good but not perfect, leading to some images being slightly trailed. This is not a serious worry, however, implying that our effective resolution is sometimes 3 arcsec, and does not affect recognition of disturbed structure, tidal features etc., on interesting scales.

For the INT observations the chip used was the same as for the JKT observations. All galaxies were observed using a Kitt Peak *R* filter, with exposure times of either 100 or 150 s. Seeing was of moderate quality, 1–2 arcsec. The images were reduced in a similar manner to the JKT data, except that the Figaro data reduction package was used. All of the 87 control sample galaxies were observed, together with 12 of the *IRAS* galaxies for which the JKT data were of lower quality (see discussion below).

The images of the galaxy counterparts of the *IRAS* sources were examined both in the CCD data and on prints of the Palomar Sky Survey. The CCD images are of prime importance, especially as central regions, burned out on the Sky Survey, sometimes revealed double nuclei or disturbed structure. The Sky Survey material could nevertheless sometimes confirm faint features ambiguous in the CCD data, and was also needed for the nearer objects to search for companions. We classified objects into seven classes: (0) isolated, (1) distant faint companion, (2) distant bright companion, (3) near faint companion, (4) near bright companion, (5) interacting pair, (6) merger or highly peculiar. 'Near' means within 40 kpc projected distance, 'bright' means within 2 mag of the identified galaxy, 'faint' includes objects up to 4 mag fainter than the identified galaxy. The magnitudes are subjective estimates accurate to only  $\sim 1$  mag. For a close pair to be included in class (5), signs of interaction were required, e.g. tidal arms, diffuse bridges of material, plumes or other disturbed structure. To be included in class (6), we required a common envelope, or an irregular structure not easily divided into separate objects.

These decisions are, of course, largely subjective, but more detailed and clearly defined than in previous *IRAS* studies. Two biases are likely to act to some degree. First, the more luminous galaxies, being typically further away, have a higher probability of chance alignments, especially with fainter galaxies. Second, the many pairs with small separation are unresolved in

Table 1b. Properties of control sample.

Name	RA, 1950	Dec, 1950	Type	Velocity km s <sup>-1</sup>	Int class	Comments
GNA001	13 37 19.7	01 05 33	Sb	6869	5	Interacting with GNA002. Pair are
GNA002	13 37 24.6	01 05 06	Sa	6793	5	IRAS 13374+10513, L60=11.50
GNA003	13 35 52.2	00 01 34	Sab	3782	0	
GNA004	13 35 51.5	01 44 00	Sbc	12106	6	Three stellar images plus fuzz
GNA005	13 35 58.8	00 47 38	Sa	6752	2	
GNA006	13 34 14.8	01 24 30	Sbc	14237	0	
GNA008	13 36 39.1	-00 52 04	Sb	4454	0	
GNA010	13 33 39.9	-00 47 01	Sb	17859	5	IRAS 13336-4651, L60=11.74
GNA012	13 33 30.3	-01 20 13	Sc	4596	3	
GNA014	13 36 11.6	-00 09 49	Sb	3825	0	
GNA016	13 41 12.1	00 43 03	Sb	21763	3	
GNA017	13 34 33.0	00 37 20	Sbc	14246	4	
GNA020	13 35 32.7	00 16 26	Sa	6653	6	Peculiar, bar+plume, no companion
GNA022	13 35 41.4	-00 08 43	Sa	6658	5	Disturbed, several companions
GNA023	13 34 47.7	-01 29 21	Sa	6555	3	
GNA025	13 38 56.5	-00 10 07	Sa	21399	4	IRAS 13389-1015, L60=11.32
GNA026	13 45 22.5	01 01 50	Sc	27506	3	
GNA027	13 33 27.9	00 31 01	Sc	18477	0	
GNA031	13 33 47.2	-00 12 21	Sa	3810	3	
GNA032	13 37 58.1	00 15 32	Scd	3674	0	
GNA034	13 35 22.6	-01 27 54	Sb	17305	5	Interacting with fainter companion
GNA037	13 39 23.6	01 48 40	Spec	23116	6	Irregular, bar, low surf. brightness
GNA039	13 39 41.0	00 43 25	Sb	22025	1	
GNA041	13 47 46.4	00 47 43	Sb	14351	0	
GNA042	13 36 15.0	-01 26 25	Sc	4030	4	
GNA043	13 42 07.8	00 33 22	Scd	27099	1	
GNA047	13 41 36.3	00 02 06	S	21397	0	
GNA048	13 39 11.3	00 04 47	Sbc	26918	3	
GNA050	13 37 17.3	-00 30 01	S	6679	4	
GNA051	13 37 07.0	00 17 35	Sbc	25254	2	
GNA052	13 37 18.6	-00 21 29	Sbc	18431	3	
GNA054	13 40 48.6	00 52 49	Scd	7461	3	
GNA058	13 39 01.4	00 34 34	Spec	21559	6	Double nucleus, third galaxy
GNA059	13 42 46.2	-01 43 05	Sc	22847	3	
GNA061	13 37 18.3	-00 56 43	S	15752	3	
GNA064	13 34 44.9	-01 02 28	Sd	17394	0	
GNA065	13 39 05.1	00 34 13	Scd	17499	6	Bright nucleus, irregular ring
GNA068	13 34 40.0	00 31 52	Scd	26287	0	
GNA069	13 33 22.6	-01 06 49	Sb	4879	6	Peculiar, bright companion
GNA070	13 37 58.3	-00 11 13	Scd	26250	1	
GNA074	13 44 39.5	-00 25 19	S	9204	0	
GNA080	13 40 59.2	01 22 40	Sd	11620	2	
GNB001	10 39 44.3	-00 06 54	Scd	5605	0	
GNB003	10 45 44.9	01 06 16	Sab	4832	3	
GNB006	10 44 18.1	-01 07 40	SBc	11468	1	
GNB008	10 36 38.0	-00 08 57	Sab	5665	0	
GNB010	10 41 19.3	-01 01 56	S0	8291	3	MKN 1261
GNB013	10 44 57.3	-01 13 44	Sbc	11399	0	
GNB014	10 39 19.4	01 03 17	Sdm	5580	3	
GNB015	10 36 50.2	-00 07 41	Sdm	5959	6	Two nuclei, elongated
GNB016	10 45 31.6	-01 39 47	Sbc	11299	0	
GNB018	10 42 30.5	00 22 04	Scd	11791	5	Interacting with faint companion
GNB019	10 46 43.0	00 35 38	SBc	12240	0	
GNB020	10 47 16.0	01 28 09	Scd	11673	0	
GNB021	10 42 29.8	00 41 52	Spec	7923	5	Double Nucleus

Table 1b – continued.

Name	RA, 1950	Dec, 1950	Type	Velocity km s <sup>-1</sup>	Int class	Comments
GNB023	10 39 12.4	01 38 57	Sdm	21682	3	Compact, many ft objects, cluster ?
GNB024	10 45 20.6	01 04 36	Sab	4835	0	
GNB025	10 46 18.4	01 07 03	Sab	11558	0	
GNB026	10 33 40.5	00 06 00	S	8031	0	
GNB028	10 41 25.7	-00 19 33	PR?	18291	6	Two bright nuclei
GNB032	10 47 25.4	00 37 03	Scd	11115	2	
GNB033	10 45 11.0	-00 06 48	Scd	11610	6	Bright nucleus, two rings, ft compn
GNB034	10 45 33.7	00 25 51	Sab	11842	1	
GNB035	10 46 51.1	-00 09 55	Sbc	11466	3	
GNB036	10 41 11.4	-00 09 38	Sab?	11439	0	
GNB038	10 42 50.5	-00 59 57	COMP	11608	0	
GNB042	10 46 51.5	01 16 33	PR?	20230	6	Double nucleus, third galaxy
GNB043	10 40 09.0	-00 05 10	Spec	5481	0	
GNB044	10 38 17.9	-00 39 41	Sa	11403	0	
GNB045	10 33 31.8	00 21 40	Scd	28971	2	
GNB046	10 39 48.0	01 23 19	Scd	21368	0	
GNB048	10 47 08.6	-01 31 12	Sbc	11240	0	
GNB049	10 38 55.1	00 40 49	Scd	24657	2	
GNB050	10 47 29.0	01 25 21	Scd	11745	0	
GNB052	10 47 22.9	-01 36 57	Sab	11159	2	
GNB053	10 39 01.1	-01 49 23	Sb	17849	3	
GNB056	10 46 31.1	-00 24 15	Sab	11593	0	
GNB057	10 40 48.5	01 14 18	Sab	21457	3	
GNB058	10 46 31.0	-01 29 38	Sa	15931	0	
GNB059	10 43 30.0	-00 49 53	Sab	10983	0	
GNB062	10 37 00.8	00 00 26	S	5654	0	
GNB069	10 40 58.6	01 16 54	Sbc	21700	1	
GNB073	10 37 09.3	-00 26 50	S0/SA	8114	2	
GNB075	10 42 42.7	01 43 50	S	5019	5	Detached plume
GNB076	10 40 41.1	-00 49 32	Sab	11420	1	
GNB091	10 47 14.9	-01 41 09	Sb	11119	0	
GNB098	10 47 19.7	-00 07 43	Sab	11463	0	

Note: The name, position, type and heliocentric absorption velocity of each galaxy are transcribed from Peterson *et al.* (1986). The interaction class and comments are our judgements, as described in the text.

Table 2a. Distribution with interaction class.

	Number in interaction class :								fraction in 5+6
	0	1	2	3	4	5	6		
(a) CONTROL all galaxies	33	7	8	17	4	8	10	21% +/- 5%	
(b) CONTROL excl. IRAS sources	33	7	8	17	3	5	10	18% +/- 5%	
(c) IRAS log(L60) < 11.0	13	2	2	0	0	2	0	11% +/- 8%	
(d) IRAS log(L60) > 11.0	13	2	2	3	2	13	6	46% +/- 13%	
(e) IRAS log(L60) > 11.5	7	2	1	2	1	7	4	46% +/- 20%	

**Table 2b.** Statistical comparison of various pairs of samples.

CONTROL	vs	IRAS, $\log(L60) < 11.0$	P = 43%
CONTROL	vs	IRAS, $\log(L60) > 11.0$	P < 1%
CONTROL	vs	IRAS, $\log(L60) < 11.5$	P = 23%
CONTROL	vs	IRAS, $\log(L60) > 11.5$	P < 1%
IRAS, $\log(L60) > 11.0$	vs	IRAS, $\log(L60) < 11.0$	P < 1%
IRAS, $\log(L60) > 11.5$	vs	IRAS, $\log(L60) < 11.5$	P = 15%
IRAS, $\log(L60) > 11.5$	vs	IRAS, $11.0 < \log(L60) < 11.5$	P = 92%

Note: Two by two tables were formed, with numbers in class 0–4, 5–6, for each of two samples, and a  $\chi^2$  test performed. The number given is the probability of getting a  $\chi^2$  as large or larger on the hypothesis of no difference in distribution between the two samples. When using the control sample for this test, the *IRAS* sources in that sample were excluded.

the *IRAS* 60- $\mu$ m aperture, so there will be a flux contribution from both galaxies. In later sections we discuss the robustness of our conclusions in the light of this bias.

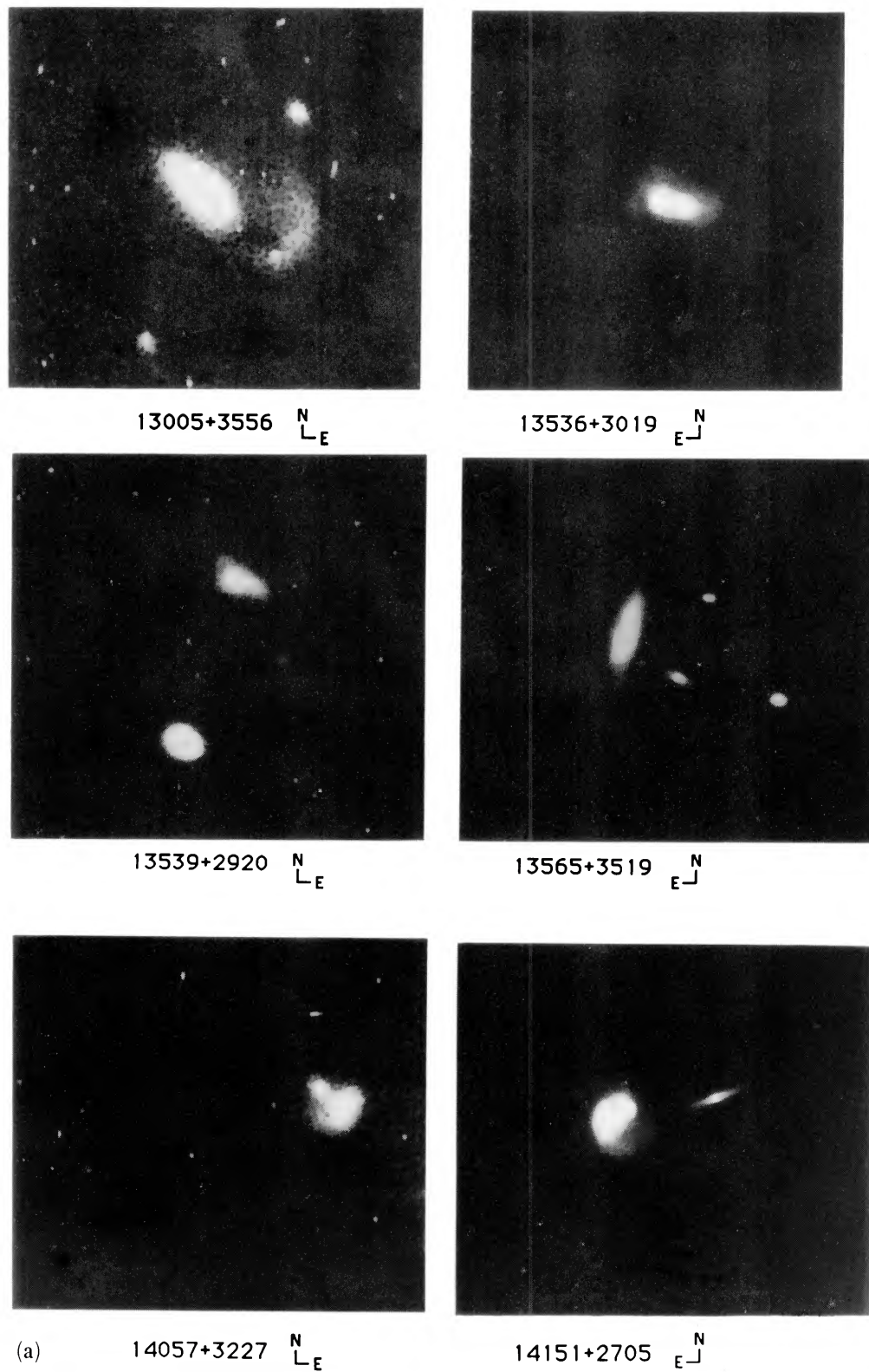
A further bias could arise from the fact that, while all the control sample galaxies were observed with the INT, only 12 of the *IRAS* galaxies were; the remaining 48 having been observed only with the JKT. Two galaxies, which on the basis of the JKT images were classified as having close companions but no interaction, were classified as interacting on the INT images. Thus the possibility arises that the five remaining *IRAS* galaxies classified as having close companions but with no interaction (class 3 or 4) might also be reclassified on the basis of improved data. We do not believe this will happen, because the *IRAS* galaxies selected for re-observation were precisely those for which the JKT data were of lower quality. For the remainder we believe the JKT data are of sufficient quality to have revealed any significant interaction.

There is a sense in which any two close galaxies ( $< 40$  kpc separation) are likely to be interacting at *some* level, and there were several cases amongst the control sample where two close galaxies showed some slight peculiarity, but not sufficient for us to classify them as clearly interacting. In the subsequent analysis we give results for the proportion of interacting and merging galaxies, both including and excluding the class 3 and 4 galaxies. We emphasize that for consistency this has to be done both for the *IRAS* and control samples.

Table 1 lists the classification of all objects, together with other quantities of interest, and comments. Plate 1 shows a selection of CCD images for a range of infrared luminosity and interaction class.

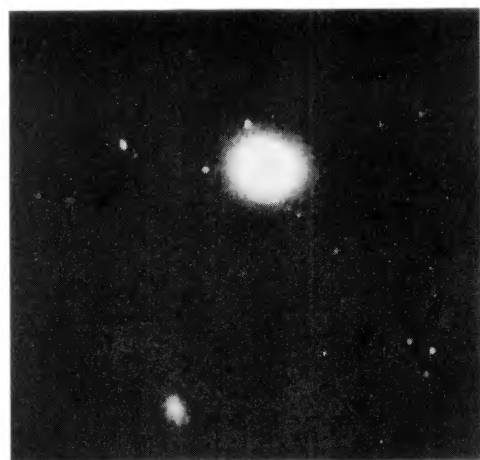
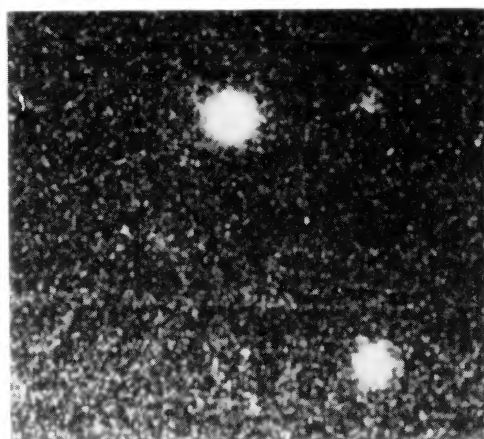
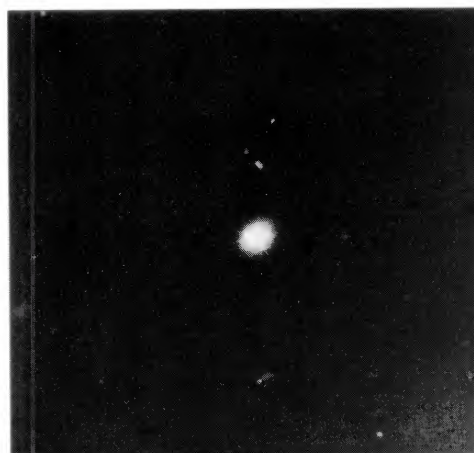
#### 4 Distribution in interaction class for *IRAS* and control samples

Table 2a gives the number in each interaction class for the control sample, and three sub-samples of the *IRAS* sample – those with  $L(60 \mu\text{m}) < 10^{11} L_{\odot}$ , with  $L(60 \mu\text{m}) > 10^{11} L_{\odot}$ , and with  $L(60 \mu\text{m}) > 3 \times 10^{11} L_{\odot}$ . Close pairs and interaction seem to be more common at higher luminosity. To examine the significance of this effect, we performed  $\chi^2$  tests on the proportion of objects in classes 5 and 6 for various pairs of samples. The results are summarized in Table 2b. The control sample and the low-luminosity *IRAS* galaxies [ $L(60 \mu\text{m}) < 10^{11} L_{\odot}$ ] are consistent with each other. High-luminosity *IRAS* galaxies [ $L(60 \mu\text{m}) > 10^{11} L_{\odot}$ ] are significantly different, at less than the 1 per cent level, from both the control sample and the low-



**Plate 1.** A selection of CCD images. For *IRAS* galaxies, the name is the standard *IRAS* catalog name, derived from the source RA and Dec in the form HHMM.M + / - DDMM. For control sample galaxies, the name is as in Peterson *et al.* (1986). (a) *IRAS* galaxies which are interacting or merging, i.e. in classes 5–6.

[facing page 340]

13111+4348  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ 13326+3417  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ 13442+2321  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ 13532+2517  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ (b) 13573+2517  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ 14575+3256  $\begin{matrix} N \\ \swarrow \searrow \\ L \quad E \end{matrix}$ **Plate 1** - *continued.* (b) *IRAS* galaxies which are not interacting or merging, i.e. in classes 0-4.

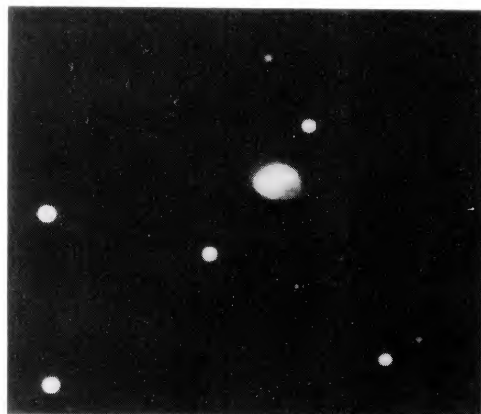
GNA 1 and 2  $\begin{matrix} N \\ E \end{matrix}$ GNA 34  $\begin{matrix} N \\ E \end{matrix}$ GNA 37  $\begin{matrix} N \\ E \end{matrix}$ GNA 58  $\begin{matrix} N \\ E \end{matrix}$ (c) GNB 15  $\begin{matrix} N \\ E \end{matrix}$ GNB 21  $\begin{matrix} N \\ E \end{matrix}$ 

Plate 1 - *continued.* (c) Galaxies from the control sample which are interacting or merging, i.e. in classes 5-6.



luminosity *IRAS* galaxies. *IRAS* galaxies with  $L(60 \mu\text{m}) > 3 \times 10^{11} L_{\odot}$  are also significantly different from the control sample, but not significantly different either from the *IRAS* galaxies with  $L(60 \mu) < 3 \times 10^{11} L_{\odot}$ , or from galaxies with  $10^{11} L_{\odot} < L(60 \mu\text{m}) < 3 \times 10^{11} L_{\odot}$ , i.e. we cannot tell whether placing the luminosity cut at higher luminosity significantly increases the observed proportion of interactions.

Another way to see this effect is to look at the luminosity distribution for different classes. Fig. 2 shows this for (a) classes 0, 1 and 2, and (b) classes 5 and 6. From a Mann-Whitney test on these distributions, their medians differ at more than 99 per cent confidence. The Mann-Whitney test also allows us to calculate a 90 per cent confidence range for the difference in median values of  $\log L(60 \mu\text{m})$ , which lies between 0.2 and 0.7.

It is then clear that interaction with a companion does indeed have a statistical link with high-luminosity IR emission, but the effect is perhaps not as dramatic as some authors have suggested. For the control sample, the proportion of objects in classes 5-6 (interacting, merging or peculiar) is  $18 \pm 5$  per cent and the fraction in classes 3-6 (near companion of any kind, or peculiar) is  $45 \pm 9$  per cent, excluding the four control sample galaxies which were seen by *IRAS*. For *IRAS* galaxies with  $L(60 \mu\text{m}) < 10^{11} L_{\odot}$ , the corresponding figures are  $11 \pm 8$  per cent for both classes 5-6 and 3-6. For *IRAS* galaxies with  $L(60 \mu\text{m}) > 10^{11} L_{\odot}$ , the corresponding figures are  $46 \pm 13$  per cent and  $59 \pm 15$  per cent. The *excess* percentage of interacting galaxies that we find amongst luminous *IRAS* galaxies, compared to what we might expect to find by chance anyway, is therefore 15-35 per cent.

For comparison, Armus *et al.* (1987) found for their rather smaller control sample that  $14 \pm 8$  per cent (4/28) are 'irregular or peculiar', while two-thirds of their sample of 39 luminous *IRAS* galaxies have a 'strange morphology'. From the contour maps which they present, we estimate that we would have classified 19 as interacting, merging or peculiar, i.e. 49 per cent, with a further 10 (26 per cent) having close companions. The two studies are therefore probably consistent with each other.

There is, however, a clear discrepancy with the study of Sanders *et al.* (1988b), who found 10/10 *IRAS* galaxies with  $L(40-120 \mu\text{m}) > 10^{12} L_{\odot}$  to be morphologically peculiar. [Note that, over a reasonable range of IR colours,  $L(40-120 \mu\text{m}) \sim 2 \times \nu L_{\nu}(60 \mu\text{m})$ .] There are several possible reasons for this disagreement: (i) Simple statistical bad luck. (ii) Sanders *et al.* studied

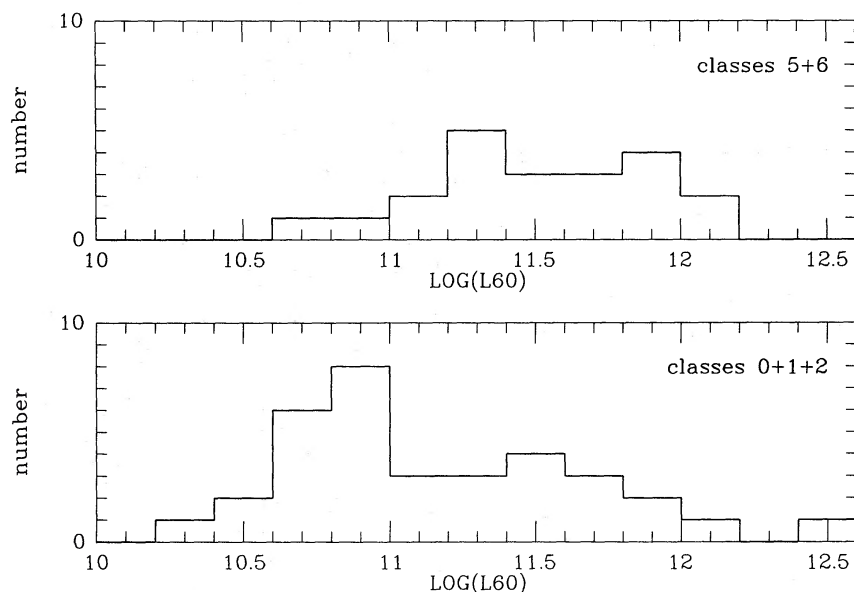


Figure 2. Distribution of 60- $\mu\text{m}$  luminosity of *IRAS* galaxies for (a) classes 0, 1 and 2, (b) classes 5 and 6.

exclusively the extremely luminous objects. As emphasized above, the statistics are too poor to justify further subdivision of our sample in luminosity, but we can at least examine the numbers. We have 15 objects with  $L(60\ \mu\text{m}) > 5 \times 10^{11} L_{\odot}$ . Of these, 6/15 are clearly interacting or merging (classes 5 and 6), and 9/15 have a companion of some kind (classes 3–6). Taking the two samples together, 16/25 have been classified as interacting or merging. (iii) Sanders *et al.* have made deeper exposures – we may have missed some evidence of peculiarity. (iv) Sanders *et al.* have no control sample – in particular it should be borne in mind that our figure of  $\sim 20$  per cent of field galaxies showing signs of interaction applies only to our modest exposures, comparable in depth to the Sky Survey. It may be that most galaxies are peculiar if one looks hard enough.

As a final check on what can be considered a normal rate of incidence of interacting pairs, we have examined Shapley–Ames galaxies in the northern hemisphere and counted how many of these are also entries in either the *Arp Catalogue* or the *Vorontsov-Velyaminov Catalogue of Interacting Galaxies*. The answer is 87 out of 639, i.e.  $14 \pm 2$  per cent. (Most objects are in both the Arp and VV catalogues. When both members of a pair were bright enough to be included in the *Shapley–Ames Catalog*, we counted both. This occurs in about 1 in 5 cases.)

Overall then, it seems that about 15 per cent of galaxies are in interacting pairs, and  $\sim 30$  per cent have close companions. For galaxies with high-IR luminosity, there is likely to be a causal link between galaxy interaction and the observed high luminosity in about 30 per cent of cases.

## 5 The confusion problem

Several of the close pairs are close enough that they will be unresolved by the *IRAS* 60- $\mu\text{m}$  aperture, so that a flux contribution from both galaxies will be present in the single point-source found. Table 1a indicates the cases where both galaxies are of comparable magnitude and separated by less than 3 arcmin in the cross-scan direction and less than 1 arcmin in the in-scan direction (including the mergers). Clearly, even if we assume that the probability of a galaxy having a given luminosity is not affected by interactions with neighbours, *IRAS* sources resulting from close pairs will appear systematically overluminous in a flux-limited survey. Can this entirely explain the observed increased probability of interactions in high-luminosity *IRAS* sources?

In Appendix A we present a detailed calculation of the expected number of pairs of galaxies amongst *IRAS* sources, based on convolving the single galaxy luminosity function from Saunders *et al.* (1989), to find the luminosity function for pairs of galaxies. There is an apparent increase in the number of pairs, but it is modest. For example, if we assume that 20 per cent of all galaxies are in pairs and use the best-fitting parameters of Saunders *et al.*, then we predict that above  $10^{11} L_{\odot}$  the apparent number of pairs will be 23 per cent. This is still significantly smaller than our estimates of the fraction of interactions and mergers (46 per cent) and all objects with close companions (59 per cent). We therefore conclude that confusion does not explain the enhanced fraction of pairs at high infrared luminosity and that it is not worthwhile making a correction for this effect.

## 6 Discussion

First, we discuss briefly the low-luminosity *IRAS* sources, i.e. those with  $L(60\ \mu\text{m}) < 10^{11} L_{\odot}$ . As can be seen from Fig. 1, these are objects with luminosities which overlap those of optically selected spirals, but are typically an order of magnitude more luminous. Rather than requiring anomalous ‘activity’ of some kind, they are likely to be larger, dustier and/or have a generally

higher star-formation rate. Our results show that interactions have little influence on producing such a modest increase in IR luminosity, but rather tend to produce very luminous starburst and/or Seyfert activity. This is reassuring for studies which use the PSC as a survey of large-scale structure within 200 Mpc (e.g. Rowan-Robinson *et al.* 1986; Lawrence *et al.* 1986; Yahil, Walker & Rowan-Robinson 1986; Meiksin & Davis 1986; Strauss & Davis 1988; Efstathiou 1988). A preponderance of interacting pairs would have indicated that the density of *IRAS* sources traces a power of the general galaxy density closer to the square of the density, but this is not the case. Further noting that the majority of the more-luminous *IRAS* sources are at large distances, the bulk of the *IRAS* galaxy survey should be a fair sample of the local Universe.

For very luminous *IRAS* galaxies, i.e. those with  $L(60\ \mu\text{m}) > 10^{11} L_{\odot}$ , we have found, in common with several other studies of activity (see Section 1), that interaction with a companion is not necessary to produce activity but does have a statistical link. It remains to be seen whether the statistical link indicates a direct causal connection (in the large minority of cases where *IRAS* galaxies clearly are interacting) or whether it results from some third parameter. Suggested causal links are of two kinds: (i) N-body calculations of the stellar dynamics of galaxies indicate that the tidal effects of interaction can perturb stellar orbits (Toomre & Toomre 1972). This could produce gas inflow to the centre, or perturb a gas disc already present in the centre, and thus induce nuclear activity or star formation (e.g. Solinger, Morrison & Markert 1977; Larson & Tinsley 1978; Roos 1981; Byrd *et al.* 1986). (ii) The kinetic energy of collision may be directly liberated in some way (Baade & Minkowski 1954; Hoyle 1960; Harwit *et al.* 1987). In this case, only mergers, as opposed to still-distinct interacting pairs, would be unusually luminous. This is clearly not so for *IRAS* galaxies, arguing against the latter as a unique explanation.

Sanders *et al.* (1988b), following on from their finding of a very high preponderance of morphological peculiarity amongst IR-luminous galaxies, discuss a detailed model in which both the luminous *IRAS* galaxy phenomenon, and the quasar phenomenon, originate in galaxy interactions. During the merger of two spiral galaxies, there may be direct collisions between molecular clouds in the two galaxies. The subsequent loss of angular momentum allows an inward flow. They argue that a nuclear starburst occurs in the early stages of a merger, followed by a quasar-like activity cocooned in dust, followed finally by a traditional quasar phase.

We should be aware that there may be an indirect connection. For radio sources, Stocke (1978) found that the correlation is with local galaxy density, rather than directly with close companions. In this case, there is a physical basis for possible third parameters – the apparent power of a radio source will depend on how stored energy is dissipated in the intergalactic medium. In the case of current nuclear activity, either quasar-like or a burst of star formation, candidates for a third parameter are less obvious.

Meanwhile, from our study we argue that a majority of IR-luminous sources are not connected with interaction, so it seems that we must consider other mechanisms for inducing activity, for example the dynamics and evolution of a central dense star cluster (Hills 1975); collision with intergalactic gas clouds (Gunn 1979); the accumulation of material in a central disc (through stellar mass loss) followed by gravitational instability at a critical density (Shields & Wheeler 1978; Bailey 1982); or the role of bars in channelling material to the nucleus of a spiral galaxy (Hawarden *et al.* 1986).

If the mechanisms differ between interacting and non-interacting *IRAS* galaxies, this may be reflected in properties other than luminosity. This is examined in more detail in Paper II, which presents optical spectroscopic data for the sample discussed in this paper, but we give a brief discussion here. First, we find that the interacting galaxies participate in a general trend of decreasing  $S(100\ \mu\text{m})/S(60\ \mu\text{m})$  with increasing  $L(60\ \mu\text{m})$ . This is probably most easily

interpreted by assuming that *IRAS* galaxies in general show a mixture of two components – relatively cool normal disc emission and warmer starburst or nuclear emission (Rowan-Robinson & Crawford 1986, 1989; Helou 1986; Leech *et al.* 1988). At a given luminosity, however, there is no apparent difference in  $S(100\ \mu\text{m})/S(60\ \mu\text{m})$  between interacting and non-interacting galaxies.

Next we consider optical spectroscopic type. Seven members of our sample are classified as Seyfert or LINER. All except one of these objects have  $L(60\ \mu\text{m}) > 10^{11} L_{\odot}$ , and 3/7 are interacting or merging, a fraction not significantly different from high-luminosity *IRAS* sources in general. It is, nevertheless, a rather higher percentage than for optically selected Seyferts – Dahari (1984) found that ~35 per cent of Seyferts have companions of any kind (as opposed to 21 per cent for a control sample), but only 7.5 per cent were ‘strongly interacting’. A possible explanation is that dynamical interaction predominantly causes starburst rather than Seyfert activity, and that some of our interacting Seyferts have been fortuitously detected because they have a concurrent starburst.

## 6 Conclusions

Low-luminosity *IRAS* galaxies [ $L(60\ \mu\text{m}) < 10^{11} L_{\odot}$ ] are interacting or merging systems in  $11 \pm 8$  per cent of cases. This fraction is similar to that in an optically selected control sample,  $18 \pm 5$  per cent, and to that of Shapley–Ames galaxies in the Arp and VV Catalogues,  $14 \pm 2$  per cent, indicating that low-luminosity objects are not unusual in this respect. At high luminosities [ $L(60\ \mu\text{m}) > 10^{11} L_{\odot}$ ] the percentage of interacting and merging systems is  $46 \pm 13$  per cent. This indicates a clear statistical link between interactions and IR activity, but interaction does not seem to be the most common cause of activity. Our criteria may have led to us missing some interacting objects, but this should apply equally to the control sample. Counting objects with close companions, regardless of whether we have seen signs of interaction (i.e. those in our interaction classes 3–6), we find 59 per cent of luminous *IRAS* galaxies in this category, and 45 per cent of the optically selected control galaxies. We find therefore that the *excess* of luminous *IRAS* galaxies which are interacting, compared to those expected by chance, is in the range 15–35 per cent.

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#### Appendix A: Calculation of the expected number of pairs of galaxies in a flux-limited survey with large beam

We take the null hypothesis to be that the presence of a close neighbour has no effect on the probability of a galaxy having a given luminosity,  $L$ . We further make the simplifying assumption that each galaxy is either single, or one of a pair of galaxies, and that in the latter case, the

*IRAS* detectors see a single source, with both galaxies contributing to the observed flux. For the most nearby galaxies, i.e. those appearing in the *IRAS* catalog with very low luminosities, this was clearly not the case. However, as our conclusion is that the effects described here do not explain the excess of interacting pairs at high luminosity, the possible errors caused by this simplifying assumption do not matter.

We define  $\Phi(L)$  as the number of galaxies per unit volume with luminosity less than  $L$ , the total space density as  $\Phi$ , and the differential luminosity function as  $\phi(L) = d\Phi/dL$ . We can express this in probability terms,  $p(L) = \phi(L)/\Phi$ . Next we assume that a fraction  $F$  of all galaxies are in pairs. Then the space density of single galaxies is  $\Phi_1 = (1 - F)\Phi$ , and the space density of pairs (as opposed to galaxies within pairs) is  $\Phi_2 = \Phi F/2$ .

What we wish to find is the luminosity function for pairs of galaxies,  $\phi_2(L)$ , and thus the net luminosity function of *IRAS* sources,  $\phi_{\text{net}}(L) = \phi_1(L) + \phi_2(L)$ , which is  $(1 - F)\phi(L) + \phi_2(L)$ . The probability of a pair of galaxies having luminosity  $L$  between them is given by summing the probabilities of all the combinations of two galaxies with individual luminosities adding up to  $L$ , i.e. by the convolution

$$p_2(L) = \int_0^L p(L') p(L - L') dL'$$

and then  $\phi_2(L) = \Phi p_2(L) F/2$ .

We first investigated numerically the general effect of such a convolution on the shape of the luminosity function. For power-law luminosity functions,  $\phi(L) = KL^{-\alpha}$ , flat power laws become flatter and steep power laws become steeper, with the crossover about  $\alpha \sim 1.1$ . We next tried a Gaussian in  $\log(L)$ . In this case, the peak of the luminosity function moves to higher luminosities. In general it can be seen that, for any convergent  $\phi(L)$ , the effect must be to make the function narrower. For multiple galaxies, the central limit theorem tells us that the net probability function should approach normality.

The size and shape of the effect then depends on the luminosity function assumed. For our purposes, we used the best available 60- $\mu\text{m}$  luminosity function for *IRAS* sources, from recent work by Saunders *et al.* (1989). These authors found the analytic form

$$\phi(L) = C(L/L_*)^{-\alpha} \exp(-x^2/2\sigma^2),$$

where  $x = \log_{10}(1 + L/L_*)$ , to be a very good fit over the range  $L(60 \mu\text{m}) = 10^7 - 10^{13} L_\odot$ . Of course, this function represents the luminosity function for *IRAS* sources, rather than what we strictly want to start with, which is the luminosity function for individual galaxies. However, as we find below that the effect of pairs on the net luminosity function is small, it causes no harm to take the above function as the input  $\phi(L)$ . The best-fitting parameters (as of July 1988) are:

$$\log_{10}(L_*) = 9.0 \pm 0.1 L_\odot,$$

$$\alpha = 1.05 \pm 0.1,$$

$$\sigma = 0.75 \pm 0.05, \text{ and}$$

$$C = 3 \times 10^{-3} h_{50} \text{ Mpc}^{-3}.$$

Our calculations were actually performed in units such that  $C = L_* = 1$ .

One problem is that this analytic form is marginally divergent, so we cannot form the probability version of the luminosity function. (Presumably the real luminosity function does finally converge.) We can perform the convolution (equation A1) using  $\phi(L)$  instead of  $p(L)$ , down to some lower limit  $L_{\text{low}}$ . We find empirically that the choice of  $L_{\text{low}}$  has little effect on

the shape of  $\phi_2(L)$  well above  $L_{\text{low}}$ , but, of course, the true  $\phi_2(L)$  is unknown by a constant factor. However, we can normalize  $\phi_2(L)$  as outlined below.

At very high luminosities, the probability of a galaxy having such a high luminosity is small. In a pair with high luminosity, essentially all the luminosity will therefore be from one unusual galaxy, but the presence of two galaxies increases the chance that one or the other will be unusual. If the probability that a galaxy has luminosity greater than  $L$  is  $P$ , the probability that one or the other of the pair has luminosity greater than  $L$  is  $Q = 1 - (1 - P)^2$ . For the highest-luminosity objects  $P \ll 1$ , and so  $Q \sim 2P$ . This will be true for all  $L$  above some suitably high value, so above this value it will also be true differentially, i.e.  $p_2(L) = 2p(L)$ . Note that, although pairs have double the probability of being highly luminous, each pair makes only one *IRAS* source, so that at very high luminosities, the fraction of *IRAS* sources which are seen to be pairs of galaxies is the same as the fraction of all galaxies which are in pairs, i.e.  $\phi_2(L) \sim F\phi(L)$ .

The scheme actually used was then as follows:

(a) input assumed  $\phi(L)$  for galaxies,

(b)  $\phi_1(L) = (1 - F)\phi(L)$

(c)  $\psi(L) = \int_{L_{\text{low}}}^L \phi(L') \phi(L - L') dL'$ , with  $L_{\text{low}} = 10^{-3}$  (i.e.  $\sim 10^6 L_{\odot}$ ), and

(d)  $\phi_2(L) = \psi(L) F\phi(L_{\text{high}}) / \psi(L_{\text{high}})$ , with  $L_{\text{high}} = 10^4$  (i.e.  $\sim 10^{13} L_{\odot}$ ).

We then calculated the expected observed number distribution in a flux-limited survey

$$dN/d(\log L) = KV_{\text{max}}(L) \phi(L) = KL^{5/2} \phi(L)$$

for  $\phi_2$ , and  $\phi_{\text{net}} = \phi_1 + \phi_2$ .

Our analysis of the control sample leads us to believe that  $F \sim 0.2$  is reasonable. The use of values within  $3\sigma$  of  $\alpha = 1.1$ ,  $\sigma = 0.75$ , gives results for  $\phi_{\text{net}}(L)$  not very different from  $\phi(L)$ , usually  $< 10$  per cent, always less than 40 per cent different at any point, such that a fit to  $\phi_{\text{net}}(L)$  instead of  $\phi(L)$  would give parameters still within the original fit errors, justifying the use of  $\phi(L)$  from Saunders *et al.* as the luminosity function for galaxies rather than *IRAS* sources. The real quantity of interest is the apparent fraction of pairs in the survey, i.e.  $N_2(L) / N_{\text{net}}(L)$ . This quantity is fixed by our normalization to be equal to  $F$  at  $L = 10^4$  (i.e.  $\sim 10^{13} L_{\odot}$ ). It always seems to be greater than  $F$  at medium  $L$ , and is very sensitive to choice of  $\alpha$  at very low  $L$ . The numbers appearing in a flux-limited survey at low  $L$  are, however, very small – the peak of  $dN/d(\log L)$  is at  $L \sim 60$  (i.e.  $\sim 6 \times 10^{10} L_{\odot}$ ). More robust quantities are the numbers appearing above and below  $L = 100$ , i.e. roughly corresponding to the division at  $L(60 \mu\text{m}) = 10^{11} L_{\odot}$  used in the main body of this paper.

**Table A1.** Predicted percentage of *IRAS* sources which are in pairs, below/above  $10^{11} L_{\odot}$ , for various values of  $\alpha$  and  $\sigma$ , assuming  $F = 0.2$ .

Value of $\alpha$	Percent below/above $10^{11}$		
0.75	32/28	31/27	28/34
1.05	29/24	28/23	27/22
1.35	25/21	24/21	24/21
Value of $\sigma$	0.6	0.75	0.9

**Table A2.** Predicted percentage of *IRAS* sources that are pairs, below/above  $10^{11} L_{\odot}$ , for various values of  $F$ , assuming  $\alpha = 1.05$  and  $\sigma = 0.75$ .

	Fraction below $10^{11}$	Fraction above $10^{11}$
$F=0.1$	14%	12%
$F=0.15$	21%	18%
$F=0.2$	28%	23%
$F=0.5$	60%	55%

Tables A1 and A2 show the resulting fraction of pairs amongst *IRAS* sources, for various input parameters. For  $F=0.2$ , within the  $3\text{-}\sigma$  range of the Saunders *et al.* parameters, the apparent increase in the number of pairs above  $\sim 10^{11} L_{\odot}$  is small,  $< 8$  per cent, and relative to the number of pairs below  $10^{11} L_{\odot}$ , the number of pairs above  $10^{11} L_{\odot}$  actually decreases. We therefore conclude that the observed high fraction of pairs of galaxies amongst high-luminosity *IRAS* sources is not due to confusion, and that any correction for this effect is small, i.e. smaller than the statistical uncertainties of our estimates.