

# The infrared compactness-temperature relation for quiescent and starburst galaxies<sup>★</sup>

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## ABSTRACT

**Context.** *IRAS* observations show the existence of a correlation between the infrared luminosity  $L_{\text{IR}}$  and dust temperature  $T_{\text{d}}$  in star-forming galaxies, in which larger  $L_{\text{IR}}$  leads to higher dust temperature. The  $L_{\text{IR}}-T_{\text{d}}$  relation is commonly seen as reflecting the increase in dust temperature in galaxies with higher star formation rate (SFR). Even though the correlation shows a significant amount of dispersion, a unique relation has been commonly used to construct spectral energy distributions (SEDs) of galaxies in distant universe studies, such as source number counting or photometric redshift determination.

**Aims.** In this work, we introduce a new parameter, namely the size of the star-forming region  $r_{\text{IR}}$  and lay out the empirical and modelled relation between the global parameters  $L_{\text{IR}}$ ,  $T_{\text{d}}$  and  $r_{\text{IR}}$  of IR-bright non-AGN galaxies.

**Methods.** *IRAS* 60-to-100  $\mu\text{m}$  color is used as a proxy for the dust temperature and the 1.4 GHz radio continuum (RC) emission for the infrared spatial distribution. The analysis has been carried out on two samples. The first one is made of the galaxies from the 60  $\mu\text{m}$  flux-limited *IRAS* Revised Bright Galaxy Samples (RBGS) which have a reliable RC size estimate from the VLA follow-ups of the *IRAS* Bright Galaxy Samples. The second is made of the sources from the 170  $\mu\text{m}$  ISOPHOT Serendipity Sky Survey (ISOSSS) which are resolved by the NRAO VLA Sky Survey (NVSS) or by the Faint Images of the Radio Sky at Twenty-cm survey (FIRST).

**Results.** We show that the dispersion in the  $L_{\text{IR}}-T_{\text{d}}$  diagram can be reduced to a relation between the infrared surface brightness and the dust temperature, a relation that spans 5 orders of magnitude in surface brightness.

**Conclusions.** We explored the physical processes giving rise to the  $\Sigma_{\text{IR}}-T_{\text{d}}$  relation, and show that it can be derived from the Schmidt law, which relates the star formation rate to the gas surface density.

**Key words.** galaxies: fundamental parameters – galaxies: starburst – infrared: galaxies – radio continuum: galaxies

## 1. Introduction

The sky survey by the *IRAS* satellite (Neugebauer et al. 1984) led to the discovery of strong connections between global parameters of galaxies in the local universe. Among them, the 60-to-100  $\mu\text{m}$  flux density ratio  $R(60/100)$  versus  $L_{\text{IR}}$  *IRAS* diagram (Soifer et al. 1987) exhibits a large dispersion. The quantities  $L_{\text{IR}}$  and  $R(60/100)$  of quiescent and starburst galaxies are fundamental parameters for the study of star formation. The first one represents the energy absorbed and reprocessed by dust and is related to the star formation rate. The second parameter traces the dust temperature  $T_{\text{d}}$  and also provides an estimate of the star formation efficiency as defined by the SFR per unit of gas mass (Young et al. 1986; Chini et al. 1992).

The first attempts to relate the infrared surface brightness (which we also refer to as infrared compactness) to the dust temperature were hampered by the lack of sufficient infrared spatial resolution. Devereux (1987) used ground-based small-beam observations at 10  $\mu\text{m}$  and compared them to the large-beam

12  $\mu\text{m}$  *IRAS* flux densities to estimate the compactness of optically bright galaxies. He showed that the ratio between the small-beam and large-beam flux densities is correlated with the global *IRAS* 12-to-25  $\mu\text{m}$  flux density ratio which also traces the dust temperature. The main limitation of this work is the use of a rough compactness estimator that can not be easily related to physical parameters and thus no concluding relationship was derived.

Other similar attempts showed that the optical surface brightness (Phillips & Disney 1988) and the infrared surface brightness derived from  $H_{\alpha}$  effective area (Lehnert & Heckman 1996) of IR bright galaxies increase with  $R(60/100)$ . However, the quantitative understanding of these correlations is not straightforward because the optical surface brightness results from stars that may not be related to the dust emission and because in the second study, in addition to the small size of the sample (32 galaxies), the authors used  $H_{\alpha}$  maps to estimate the star-forming region size without applying an extinction correction which turns out to be crucial (Chaniai et al., in prep.).

Wang & Helou (1992) made use of the extinction-free 1.4 GHz radio continuum (RC) size estimators to show that the infrared luminosity is not proportional to the galaxy physical

<sup>★</sup> Tables 4 and 5 are only available in electronic form at <http://www.aanda.org>

area. They also showed an empirical relation between the mean RC surface brightness  $\Sigma_{RC}$  and luminosity  $L_{RC}$ , but they did not consider the IR color variations within their sample which, as we will show in this article, is directly related to the scatter in the  $\Sigma_{RC}$ - $L_{RC}$  relation.

More recently, Roussel et al. (2001) studied a sample of galaxies mapped by the ISOCAM camera on board *ISO* (Cesarsky et al. 1996) and found a correlation between the 15-to-7  $\mu\text{m}$  flux density ratio and the 15  $\mu\text{m}$  effective surface brightness. Their sample only consists of quiescent spirals of moderate infrared luminosities and the authors only considered the circumnuclear region.

In this paper, we extend these approaches by (1) studying statistically larger samples, (2) applying a flux-limited selection criterion at 60  $\mu\text{m}$ , (3) considering fundamental parameters representative of the whole galaxy, and (4) using an extinction-independent estimator of the star-forming region size, the radio continuum angular size.

Section 2 describes the global parameters used in this paper and Sect. 3 presents the galaxy samples that are used in Sects. 4 and 5 for the analysis of the luminosity-temperature and compactness-temperature relations. The latter is modelled in Sect. 6 and discussed in Sect. 7.

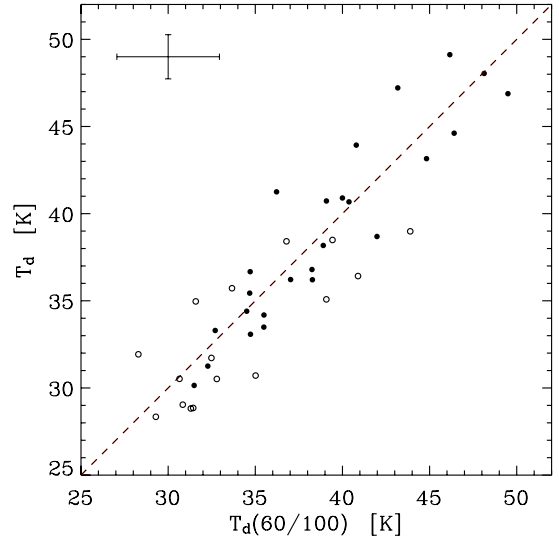
## 2. Parameter definitions and estimations

### 2.1. The dust temperature

The temperature of the dust in a given galaxy is subject to spatial variations (Dale et al. 1999) that show a decrease from the center outwards. So, the attempt to describe the global thermal emission of the dust with one or two modified blackbodies may be questioned. However, submillimeter observations at 450  $\mu\text{m}$  and 850  $\mu\text{m}$  (Dunne et al. 2000; Dunne & Eales 2001; Vlahakis et al. 2005) have shown that the *global* emission at these wavelengths, which trace cold dust, does correlate with the global  $R(60/100)$ , which traces warmer dust. This finding suggests that inner and outer emissions may be bound together. Such a property would likely be the manifestation of the star formation regulation occurring on a global scale, as it appears in the Schmidt law (1959) or in relations which involve the galaxy rotation curve such as the Toomre's stability criterion (1964) and the law by Kennicutt (1998).

The often used two-component model does not reflect the fact that a single free parameter such as  $R(60/100)$  suffices to describe the SEDs of galaxies whose infrared emission arises from star formation (Dale et al. 2001; Dale & Helou 2002). As a matter of fact, Serjeant & Harrison (2005) constructed a library of two-components IR templates, but to do so, they parametrized the temperatures and the relative weights with  $R(60/100)$ . By contrast, using a single blackbody with a constant emissivity index certainly does not provide the most accurate description of the SED, but it may supply a more profound insight on the global state of the dust in a galaxy.

We thus *define* for this paper the effective dust temperature  $T_d$  of a galaxy as the temperature of the modified blackbody of fixed emissivity index  $\beta$  which best fits the galaxy rest-frame SED between 50 and 1000  $\mu\text{m}$ . The SCUBA Local Universe Galaxy Survey (Dunne et al. 2000) is to date the largest homogeneous set of infrared bright galaxies observed at 850  $\mu\text{m}$ . The authors derived a mean emissivity index  $\langle\beta\rangle = 1.3$  with a standard deviation of 0.2. A subsample was then observed at 450  $\mu\text{m}$  (Dunne & Eales 2001) but the authors did not publish their single-temperature analysis, although they do state that



**Fig. 1.** Temperature of the modified blackbodies ( $\beta = 1.3$ ) fitted to the 60 and 100  $\mu\text{m}$  *IRAS* flux densities (abscissæ) and to additional far-infrared and submillimeter observations (ordinates). The SLUGS 450  $\mu\text{m}$  subsample and the SINGS subsample are represented with filled and open circles. The dashed line is the unity line and the average uncertainties are shown in the upper left corner.

this model cannot be ruled out, and instead favoured the analysis of the two-component model which offers one additional free parameter. By excluding galaxies with an active galactic nucleus (AGN) from their 450  $\mu\text{m}$  sample and by taking the flux densities tabulated in their article, we found a similar value of  $\langle\beta\rangle = 1.38$  with a sample standard deviation of 0.17. Since only 2 out of 25 galaxies have a reduced  $\chi_r^2 > 2$ , the single-temperature model provides a reasonable fit in most cases and we adopted the fiducial value  $\beta = 1.3$  in this paper.

The next step is to check that it is possible to easily associate an estimator to the previously defined effective dust temperature, the estimator of choice being the color  $R(60/100)$  due to its matchless availability in the local universe. We have already noted that the  $R(60/100)$  parameter can characterize to some extent the whole infrared SED of normal and starburst galaxies, but its precision still has to be determined. For two sets of non-AGN galaxies described in Tables 1 and 2, we compared the effective dust temperatures exclusively derived from the 60 and 100  $\mu\text{m}$  *IRAS* flux densities to the temperatures that are derived from additional far-infrared (FIR) and submillimeter observations. The two sets are the SCUBA SLUGS 450  $\mu\text{m}$  subsample (Dunne & Eales 2001) and the galaxies observed by *Spitzer* at 70 and 160  $\mu\text{m}$  from the SINGS catalog (Kennicutt et al. 2003; Dale et al. 2005) for which submillimeter observations (800 or 850  $\mu\text{m}$ ) were available in the literature. We completed the second set with far-infrared flux densities mainly from ISOPHOT (Lemke et al. 1996) and the Kuiper Airborne Observatory. The results are shown in Fig. 1 and confirm  $R(60/100)$  as an estimator of the effective dust temperature. The standard deviation is 2.8 K, which is small enough to validate the use of  $R(60/100)$  to estimate the effective dust temperature in our study.

### 2.2. The IR luminosity

The infrared luminosity is estimated from the bolometric luminosity of the best-fitting blackbody modified by a  $\lambda^{-1.3}$  emissivity function. As a consequence, it is a measure of the IR emission of the big dust grains in thermal equilibrium and it

**Table 1.**  $R(60/100)$  as an effective temperature estimator: the SCUBA 450  $\mu\text{m}$  SLUGS subsample.

Name	Morphology	$D$	$\log L_{\text{IR}}$	$f_v(60 \mu\text{m})$	$f_v(100 \mu\text{m})$	$T_d(60/100)$	$T_d$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
UGC 903	Sc	33.16	10.32	7.78	15.45	$35.5 \pm 2.7$	$33.5 \pm 1.0$
NGC 958	SBc	76.36	11.00	5.85	15.08	$31.5 \pm 2.2$	$30.1 \pm 0.7$
UGC 2369 S	Sbc	121.90	11.39	8.07	11.18	$40.4 \pm 3.3$	$40.7 \pm 1.5$
UGC 2403	SBa	53.78	10.68	7.72	12.06	$38.3 \pm 3.1$	$36.2 \pm 1.2$
NGC 2856	Sc	40.08	10.32	5.73	10.15	$37.0 \pm 2.9$	$36.2 \pm 1.3$
NGC 2990	Sc	47.18	10.43	5.16	9.61	$35.5 \pm 2.7$	$34.2 \pm 1.1$
UGC 5376	Sd	31.28	10.10	5.36	10.41	$34.7 \pm 2.6$	$33.1 \pm 1.0$
Arp 148 E	Irr	143.20	11.45	6.38	10.30	$38.9 \pm 3.1$	$38.2 \pm 1.4$
Zw 247.020	Sa	107.70	11.16	6.01	8.47	$40.8 \pm 3.4$	$43.9 \pm 2.0$
I Zw 107	Pair	168.70	11.70	9.02	10.00	$46.4 \pm 4.2$	$44.6 \pm 1.9$
NGC 5962	Sc	32.17	10.41	8.93	21.82	$32.3 \pm 2.3$	$31.3 \pm 0.8$
NGC 6052	Pair	70.42	10.86	6.79	10.57	$38.3 \pm 3.1$	$36.8 \pm 1.3$
NGC 6181	SABc	30.70	10.36	8.94	20.83	$32.7 \pm 2.4$	$33.3 \pm 1.0$
NGC 7541	SBbc	30.09	10.66	20.08	41.87	$34.5 \pm 2.6$	$34.4 \pm 1.0$
NGC 520 S	Sa	30.22	10.78	31.52	47.37	$39.1 \pm 3.2$	$40.7 \pm 1.3$
UGC 2982	SABc	67.57	10.97	8.39	16.82	$34.7 \pm 2.6$	$35.4 \pm 1.0$
NGC 2623	Sa	77.43	11.44	23.74	25.88	$46.2 \pm 4.2$	$49.1 \pm 1.8$
NGC 3110	SBb	73.48	11.17	11.28	22.27	$34.7 \pm 2.6$	$36.7 \pm 1.1$
IRAS 10173+0828		198.70	11.63	5.61	5.86	$49.5 \pm 4.6$	$46.9 \pm 1.7$
IRAS 10565+2448		176.30	11.87	12.10	15.01	$43.2 \pm 3.7$	$47.2 \pm 1.6$
IRAS 12112+0305 NE		292.50	12.14	8.18	9.46	$48.1 \pm 4.3$	$48.0 \pm 1.8$
UGC 8387	Irr	99.99	11.55	17.04	24.38	$36.2 \pm 2.8$	$41.3 \pm 1.2$
Zw 049.057	Irr	59.06	11.20	21.89	31.53	$40.0 \pm 3.3$	$40.9 \pm 1.3$
NGC 7592	Pair	95.13	11.17	8.05	10.58	$42.0 \pm 3.5$	$38.7 \pm 1.5$
NGC 7714	Sb	38.16	10.50	11.16	12.26	$44.8 \pm 4.0$	$43.2 \pm 1.8$

Columns: (3) distance in Mpc; (4) infrared luminosity in  $L_{\odot}$  derived from the 60 and 100  $\mu\text{m}$  *IRAS* flux densities by assuming a modified blackbody of emissivity index  $\beta = 1.3$ ; (6) and (7) *IRAS* flux densities in Jy; (7) effective dust temperature and  $1\sigma$  uncertainties in K,  $\beta = 1.3$ ; (8) effective dust temperature and  $1\sigma$  uncertainties in K derived from the additional data points tabulated in Dunne & Eales (2001).

excludes the emission from smaller dust grains stochastically heated such as the polycyclic aromatic hydrocarbons. Distances for  $H_0 = 75 \text{ km s}^{-1}$  are taken from, in decreasing order of precedence: the Catalog of Neighboring Galaxies (Karachentsev et al. 2004), the Revised Bright Galaxy Sample (Sanders et al. 2003), the Surface Brightness Fluctuation survey (Tonry et al. 2001), the Nearby Galaxies Catalog (Tully 1988) and the NASA/IPAC Extragalactic Database (NED) whose redshifts were corrected for the Virgo inflow. *IRAS* flux densities are taken from, by order of precedence: the RBGS, the Large Optical Galaxies Catalog (Rice et al. 1988), the Point Source Catalogue with redshift (PSCz, Saunders et al. 2000), the Point Source Catalog (PSC, Beichman et al. 1988) and the Faint Source Catalog (FSC, Moshir et al. 1992).

### 2.3. The star-forming size

A well-known tracer of star formation, for which a wealth of large and high-resolution catalogs are available, and that is unaffected by dust extinction is the radio continuum. *Globally*, the luminosity of non-AGN galaxies at 1.4 GHz correlates with the FIR luminosity over 4 orders of magnitudes (Condon 1992; Yun et al. 2001). *Spatially*, Chanial et al. (in prep.) show that the sizes of non-AGN galaxies inferred from radio continuum observations correlate tightly with the size inferred from FIR and CO maps, even for infrared luminous galaxies, in the CO case.

In this paper, the star-forming size is estimated (Chanial et al., in prep.) as

$$r_{\text{IR}} = (0.86 \pm 0.05) r_{\text{RC}}, \quad (1)$$

where  $r_{\text{RC}}$  is the *HWHM* of the deconvolved RC emission (see Sect. 3). The *HWHM* is chosen to be along the major axis, to account for the galaxy inclination at a first order.

### 2.4. Infrared surface brightness

We define the observed infrared surface brightness by the formula

$$\Sigma_{\text{IR}} = \frac{L_{\text{IR}}}{2\pi r_{\text{IR}}^2}. \quad (2)$$

The factor  $\frac{1}{2}$  has been introduced to provide a better estimate of the IR emission from the effective area  $\pi r_{\text{IR}}^2$ , where  $r_{\text{IR}}$  is the observed *HWHM* maximum of the emission along the major-axis, because for axisymmetric Gaussian profiles (face-on galaxies case), the half-light radius  $r(\frac{1}{2}) = \sqrt{2 \ln 2} \sigma$  is equal to the *HWHM*.

## 3. Sample definitions

Soifer & Neugebauer (1991) showed that the complete 100  $\mu\text{m}$  flux-limited subsample of a complete 60  $\mu\text{m}$  flux-limited sample has a colder average dust temperature, which implies that the  $L_{\text{IR}}-T_d$  relation is biased by the wavelength at which a sample is selected (see also Blain et al. 2004). Furthermore, cold ultraluminous infrared galaxies falling off this relation have been discovered in the 170  $\mu\text{m}$  FIRBACK survey (Chapman et al. 2002) and in submillimeter surveys (Chapman et al. 2005).

**Table 2.**  $R(60/100)$  as an effective temperature estimator: the *Spitzer* SINGS subsample.

Name	Morphology	$D$	$\log L_{\text{IR}}$	$f_{\nu}(60 \mu\text{m})$	$f_{\nu}(70 \mu\text{m})$	$f_{\nu}(100 \mu\text{m})$	$f_{\nu}(160 \mu\text{m})$	$\lambda$	$f_{\nu}(\lambda)$	Refs.	$T_{\text{d}}(60/100)$	$T_{\text{d}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
NGC 337	SBcd	21.6	10.04	9.07	8.83	20.11	18.30	850	0.35	1	$32.8 \pm 2.4$	$30.5 \pm 1.1$
NGC 2798	SBa	27.8	10.52	20.60	14.70	29.69	18.45	850	0.19	1	$39.4 \pm 3.2$	$38.5 \pm 1.6$
NGC 2976	Sc	3.6	8.68	13.09	16.99	33.43	46.81	850	0.61	1	$30.8 \pm 2.2$	$29.0 \pm 1.2$
NGC 3190	Sa	24.1	9.80	3.33	4.34	9.84	13.19	850	0.19	1	$29.3 \pm 2.0$	$28.3 \pm 0.9$
Mrk 33	Sm	26.8	9.83	4.79	3.34	5.49	3.46	850, 850	0.05, 0.04	2, 1	$43.9 \pm 3.9$	$39.0 \pm 1.5$
NGC 3521	SABb	6.8	9.81	49.19	49.85	121.80	206.70	850	2.11	1	$31.3 \pm 2.2$	$28.8 \pm 1.2$
NGC 4254	Sc	15.3	10.39	37.46	39.02	91.86	131.80	160, 350, 360 450, 800, 850	78, 7.8, 16 3.8, 0.6, 1.01	3, 4, 3 4, 4, 1	$31.6 \pm 2.2$	$35.0 \pm 1.0$
NGC 4321	SABb	15.2	10.25	26.00	32.28	68.37	128.40	160, 850	46, 0.88	3, 1	$30.7 \pm 2.1$	$30.5 \pm 1.2$
NGC 4536	SABb	14.9	10.15	30.26	22.49	44.51	54.39	850	0.42	1	$39.1 \pm 3.2$	$35.1 \pm 1.6$
NGC 4631	SBcd	7.7	10.08	85.40	98.78	160.10	269.00	180, 450, 450 450, 850, 850 850, 870	121, 25.06, 30.7 18, 5.253, 5.73 1.89, 3.78	5, 6, 1 5, 6, 1 5, 7	$35.0 \pm 2.7$	$30.7 \pm 0.7$
NGC 5195	SBO	7.7	9.35	15.22	10.85	31.33	12.34	850	0.26	1	$33.7 \pm 2.5$	$35.7 \pm 1.5$
NGC 5713	SABb	26.7	10.54	22.10	17.23	37.28	34.77	180, 450, 800 850, 850, 850	16, 0.889, 0.102 0.359, 0.57, 0.43	5, 8, 8 9, 1, 5	$36.8 \pm 2.9$	$38.4 \pm 1.2$
NGC 5866	S0-a	15.3	9.65	5.26	6.66	16.98	16.53	180, 450, 850	10.5, 0.79, 0.14	5, 1, 1	$28.3 \pm 1.9$	$31.9 \pm 0.8$
NGC 6946	SABc	5.9	10.08	129.80	177.90	290.70	498.40	60, 60, 100 160, 200, 200 200, 450, 850	165, 115.5, 338 450, 330, 743 365.8, 18.53, 2.98	10, 11, 10 12, 12, 10 11, 1, 1	$32.5 \pm 2.4$	$31.7 \pm 0.7$
NGC 7331	Sb	13.1	10.34	45.00	56.49	110.20	164.10	60, 100, 200 450, 850	42.9, 120, 243 20.56, 2.11	10, 10, 10 1, 1	$31.4 \pm 2.2$	$28.9 \pm 0.8$
NGC 7552	Sab	21.4	10.86	77.37	45.40	102.90	86.65	850	0.8	1	$40.9 \pm 3.4$	$36.4 \pm 1.6$

Columns: (3) distance in Mpc; (4) infrared luminosity in  $L_{\odot}$  as described in Table 1; (5) and (7) *IRAS* flux densities in Jy; (6) and (8) *Spitzer* flux densities in Jy; (9) and (10) Flux densities in Jy and references for the additional far-infrared and submillimeter data: [1] Dale et al. (2005), [2] Hunt et al. (2005), [3] Stark et al. (1989), [4] Eales et al. (1989), [5] Bendo et al. (2002), [6] Stevens et al. (2005), [7] Dumke et al. (2004), [8] Chini et al. (1995), [9] Dunne et al. (2000) [10] Alton et al. (1998), [11] Tuffs & Gabriel (2003), [12] Engargiola (1991); (12) effective temperature and  $1\sigma$  uncertainties in K derived from the 60 and 100  $\mu\text{m}$  *IRAS* flux densities; (13) effective temperature and  $1\sigma$  uncertainties in K derived from all data points.

To test whether the infrared compactness-temperature relation is subject to such a bias, we performed our analysis on two samples of non-AGN galaxies selected at 60 and 170  $\mu\text{m}$ .

### 3.1. The 60 $\mu\text{m}$ selected sample

This sample has been obtained by Chanial et al. (in prep.) by matching the RBGS, which is complete for extragalactic sources with  $f_{\nu}(60 \mu\text{m}) > 5.24$  Jy and Galactic latitudes  $|b| > 5^{\circ}$ , with the two RC follow-ups around 1.4 GHz (Condon et al. 1990, 1996) of the 60  $\mu\text{m}$  flux-limited *IRAS* Bright Galaxy Samples (Soifer et al. 1987, 1989 and Sanders et al. 1995). For each *IRAS* source, one or more maps have been observed with an angular resolution ranging from  $1''.5$  to  $60''$ . Deconvolved major-axis FWHM are provided by both datasets and are derived from two-dimensional Gaussian fits to the maps.

Starting from this initial list, we applied several editing steps to ensure the reliability of the size estimates (cf. Wang & Helou 1992; Meurer et al. 1997).

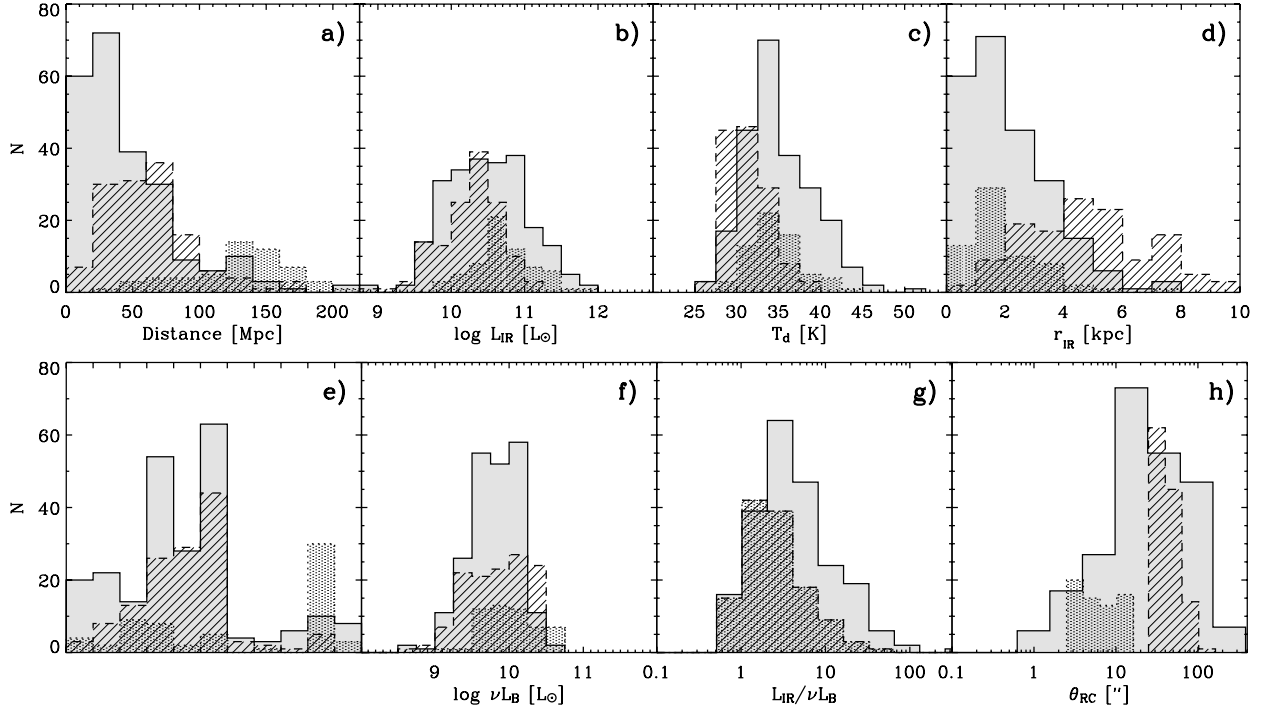
1. We retained only spatially resolved sources with angular sizes no lesser than half the radio beam *FWHM*.
2. Because at higher angular resolutions, extended emission may be missed, we retained only the radio sources that contribute to more than  $2/3$  of the total radio continuum flux, ensuring that the angular size is representative of the whole galaxy. This step also ensures that no more than one radio counterpart is retained.

3. For most of the *IRAS* sources, no more than one RC map goes through the two steps above and thus no more than one angular size estimate was deemed reliable. For the other sources, we adopted the mean value of the angular sizes.
4. Contamination by an AGN has been dealt with very conservatively by excluding galaxies satisfying any of the following optical, infrared and radio criteria: (i) position closer than  $30''$  to an AGN galaxy (including LINERs) from the extensive catalogue by Véron-Cetty & Véron (2006) or classification in NED as AGN, (ii)  $f_{\nu}(25 \mu\text{m})/f_{\nu}(60 \mu\text{m}) > 0.2$  (de Grijp et al. 1985) and (iii) low IR-to-radio ratio  $q < 1.94$  (see Yun et al. 2001).

The sample resulting from this selection process contains 232 sources. They are mostly IR-dominated spirals or interacting galaxies and their global properties are summarized in Fig. 2.

### 3.2. The 170 $\mu\text{m}$ selected sample

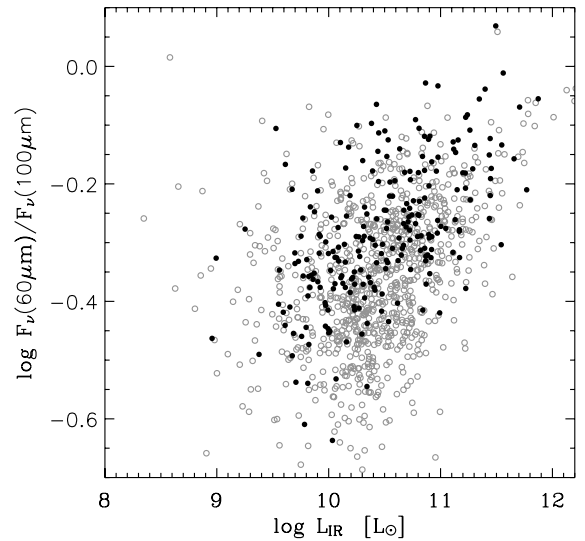
The second sample has been extracted from the ISOPHOT Serendipity Sky Survey (Stickel et al 2004), which is made of 1927 sources detected at 170  $\mu\text{m}$  by the C200 ISOPHOT detector during the slews between pointed observations. The ISOSSS covers 15% of the sky. A systematic inspection of the DSS (Digitized Sky Survey) snapshots of the sources and examining the FSC and the PSC lead us to discard 52 star identifications and 20 possible star associations, one likely planetary nebula, one extragalactic H II region, one radio source not associated with the ISOPHOT source and 7 entries that may be contaminated



**Fig. 2.** Distribution of **a)** distance, **b)** IR luminosity, **c)** effective dust temperature, **d)** IR physical radius, **e)** morphology type, **f)**  $B$ -band luminosity with  $\nu = c/0.44 \mu\text{m}$ , **g)** IR to  $B$ -band luminosity ratio and **h)** FWHM of the radio continuum emission along the major axis for the  $60 \mu\text{m}$  sample (shaded), the  $170 \mu\text{m}$  sample spatially resolved in NVSS (hatched) and FIRST (dotted). The mean distance is 46.2, 62.3 and 154 Mpc respectively, the mean  $L_{\text{IR}}$  is  $10^{10.48}$ ,  $10^{10.25}$  and  $10^{10.72} L_{\odot}$ , the mean  $T_{\text{d}}$  is 35.01, 31.36 and 34.64 K, the mean  $r_{\text{IR}}$  is 2.10, 5.10 and 2.04 kpc and the mean  $B$ -band luminosity is  $10^{9.80}$ ,  $10^{9.82}$  and  $10^{10.01} L_{\odot}$ . Morphology type and  $B$ -band luminosity are taken from the HYPERLEDA database.

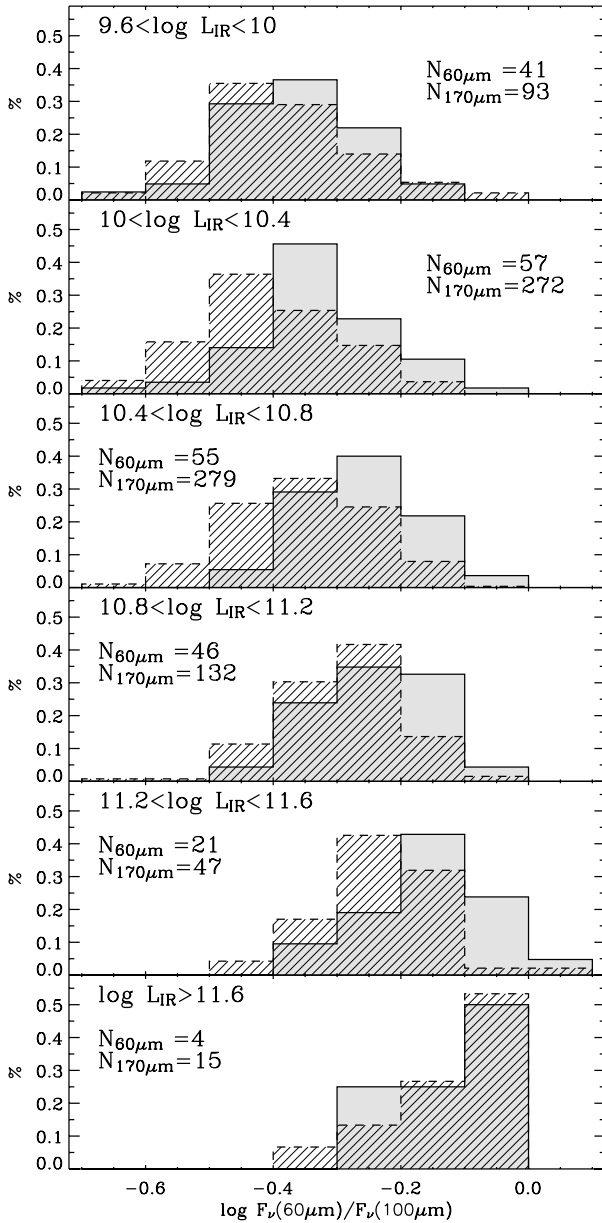
by a nearby radio source. We also excluded two offcenter duplicate entries of NGC 7331 and a source contaminated by cirrus. Before cross-correlating the ISOSSS catalog with radio catalogs, we made sure that the optical candidates taken from the HYPERLEDA database within  $2'$  of the ISOSSS position had an astrometry with one arcsecond accuracy. This work resulted in the removal of 38 duplicates, the addition of 241 new sources (including 160 stars), and 515 new positions, 426 of which were taken from the 2MASS Extended Source Catalog (Jarrett et al. 2000) the remaining ones were determined on IR POSS-2 plates, which absolute astrometry were corrected using the USNO-B1 and GSC2.2 star catalogs.

Then, we cross-correlated the optical candidates with two complementary 1.4 GHz RC surveys: the NVSS catalog (Condon et al. 1998) and the FIRST catalog (April 2003 release, Becker et al. 1995). The former has a  $45''$  resolution beam and covers 82% of the sky while the latter has a higher resolution ( $5''$ ) but a more limited sky coverage (22%). Finally, after cross-identification with the NED database, AGN candidates were removed by applying the same methodology as adopted for the  $60 \mu\text{m}$  sample. At this point, the sample contains 899 remaining sources. To avoid undersampling effects, we only retained sources whose NVSS counterpart has an angular major axis  $22'.5 < \theta_{\text{RC}} < 120''$  or whose FIRST counterpart has an angular major axis  $2'.5 < \theta_{\text{RC}} < 15''$ . NVSS and FIRST major axis  $\theta$  is derived from a two-dimensional Gaussian fit, so that sources with a complex geometry such as spirals with dominant H II regions or closely interacting pairs are unlikely to be fitted. We attempted to exclude them by rejecting those with a radio-optical position offset greater than  $\frac{1}{3}\theta_{\text{RC}}$ . We also discarded the FIRST sources that did not make up 75% of the total radio flux density, assumed to be the NVSS one.



**Fig. 3.** The rest-frame 60-to-100  $\mu\text{m}$  IRAS flux density ratio vs. the infrared luminosity. The galaxies from the  $60 \mu\text{m}$  ( $170 \mu\text{m}$ ) sample are represented by filled (open) circles. Are also plotted the sources from the  $170 \mu\text{m}$  sample for which no reliable size estimate is available.

In the final tally, the  $170 \mu\text{m}$  sample is made of 198 galaxies with reliable angular size information, of which 134 are taken from the NVSS catalog and the other 64 from the FIRST catalog. Like the  $60 \mu\text{m}$  sample, the two subsamples are mostly made of IR-dominated spirals and interacting galaxies. Their global properties are listed in the online Tables 4 and 5 and summarized in Fig. 2.



**Fig. 4.** Distribution of the rest-frame 60-to-100  $\mu\text{m}$  *IRAS* flux density ratio for 6 IR luminosity bins spanning  $10^{9.6}$  to  $10^{12} L_{\odot}$ . The shaded (hatched) histogram relates to the 60  $\mu\text{m}$  (170  $\mu\text{m}$ ) sample. The 170  $\mu\text{m}$  sample includes the sources for which no reliable size estimate is available.

#### 4. Luminosity-temperature relation

The response of the large dust grains to the heating radiation field has been studied through the  $L_{\text{IR}}-R(60/100)$  diagram. For 60  $\mu\text{m}$  flux-limited samples, it has been shown that the dust gets warmer as the FIR luminosity increases (Smith et al. 1987; Rowan-Robinson et al. 1987; Soifer et al. 1989; Soifer & Neugebauer 1991). This trend is also followed by the 170  $\mu\text{m}$  sample, but more weakly.

It has been noted that the  $L_{\text{IR}}-R(60/100)$  relation is affected by a large intrinsic dispersion, as shown in Fig. 3 for our 60 and 170  $\mu\text{m}$  samples, which is attributed to the scatter of the gas content (Soifer et al. 1987; Sanders et al. 1991). Chapman et al. (2003) carried out a phenomenological study of this dispersion in the *IRAS* 1.2 Jy survey and showed that it is key to understanding the populations of flux-limited surveys.

The systematic effect of the sample selection on the  $L_{\text{IR}}-R(60/100)$  relation, which prompted us to analyse two samples selected at different wavelengths (Sect. 3), is confirmed in Fig. 4, in which the two samples are compared in 6 IR luminosity bins. For each bin, the 170  $\mu\text{m}$  sample is colder than the 60  $\mu\text{m}$  sample, the difference being most striking for  $L_{\text{IR}}$  between  $10^{10}$  and  $10^{11.6} L_{\odot}$ .

#### 5. Compactness-temperature relation

To better understand star formation processes on a global scale, we introduced an additional parameter to the  $L_{\text{IR}}-T_{\text{d}}$  analysis, the size of the star-forming region  $r_{\text{IR}}$  derived from the FWHM of the RC profiles according to Eq. (1). This new information is shown in the  $L_{\text{IR}}-T_{\text{d}}$  diagram (Fig. 5a) by representing the galaxies from the 60  $\mu\text{m}$  sample with circles of radius proportional to  $r_{\text{IR}}$ . A systematic effect is apparent: at fixed  $L_{\text{IR}}$ ,  $R(60/100)$  increases as the physical size decreases, reflecting the qualitative fact that the dust temperature increases as the average grain-star distance decreases.

More quantitatively, we determined the plane

$$\log R(60/100) = a + b \log \frac{L_{\text{IR}}}{L_{\odot}} + c \log \frac{r_{\text{IR}}}{\text{pc}} \quad (3)$$

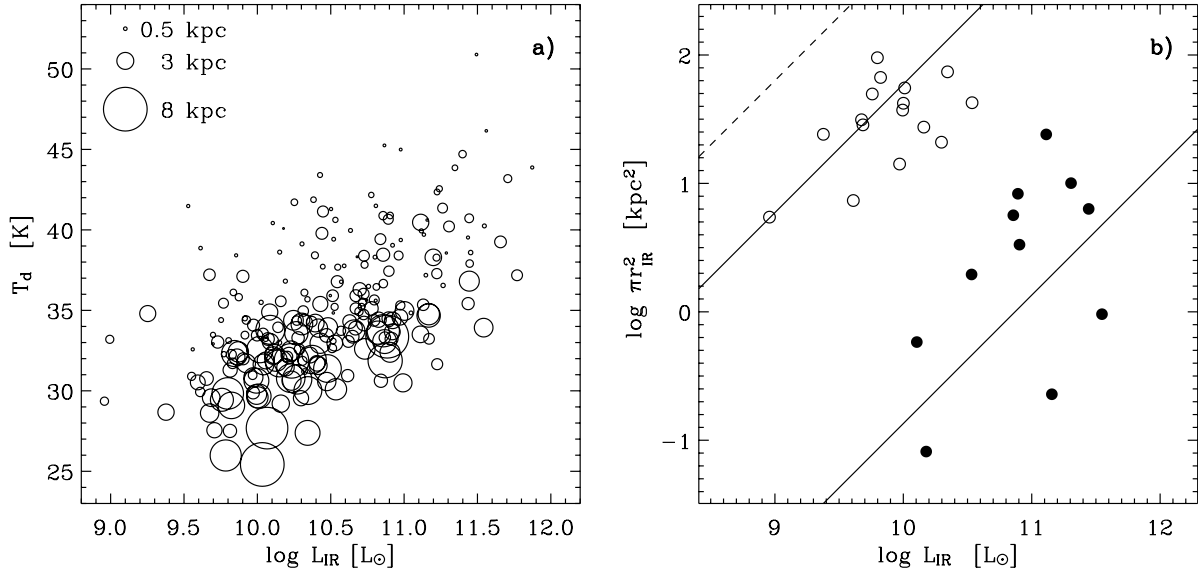
that best matches the observations in the three dimensional parameter space. The coefficients ( $a, b, c$ ) and their associated errors were derived by using bootstrap samples of the 60  $\mu\text{m}$  dataset and the resulting empirical relation is

$$\log R(60/100) = -0.663 \pm 0.095 + (0.092 \pm 0.007) \left[ \log \left( \frac{L_{\text{IR}}}{L_{\odot}} \right) - (2.09 \pm 0.24) \log \left( \frac{r_{\text{IR}}}{\text{pc}} \right) \right]. \quad (4)$$

We note that because the covariates  $r_{\text{IR}}$  and  $L_{\text{IR}}$  scale as the distance of the galaxy and as its square, the value  $c/b = -2$  may be unduly favoured by the  $\chi^2$  minimization. To check that this is not the case, we ran the bootstrap estimator on a fake 60  $\mu\text{m}$  sample, for which the values of  $L_{\text{IR}}$  and  $r_{\text{IR}}$  are unchanged, but for which the values of  $R(60/100)$  have been randomly permuted, so that the variate is uncorrelated with the covariates. In the resulting sample, the bootstrap estimation of  $c/b$  does not converge and we obtained a sample mean of  $\langle c/b \rangle = -194.3$  and a sample standard deviation of 891.2. In fact, its distribution is similar to a Cauchy (or Lorentz) distribution, for which moments do not exist. We note that such a similarity for the uncorrelated sample is not surprising, because the distribution of the ratio of two independent normal distributions is precisely a Cauchy distribution. The clear difference between the distributions of the  $c/b$  values for the real and the fake 60  $\mu\text{m}$  sample (Fig. 6) is a strong indication that the global parameters  $R(60/100)$ ,  $L_{\text{IR}}$  and  $r_{\text{IR}}$  are indeed correlated.

The resulting value of  $c/b$  is equal to  $-2$  within its uncertainties, which implies that  $R(60/100)$  scales as  $L_{\text{IR}}/r_{\text{IR}}^2$  or that for a given fixed temperature, the IR luminosity linearly scales as the IR area (Fig. 5b). This finding is non-trivial and suggests that the disk geometry comes into play. Assuming a value of  $-2$ , we performed a linear regression (bisector method)

$$\log R(60/100) = -0.783 \pm 0.019 + (0.123 \pm 0.005) \left[ \log \left( \frac{L_{\text{IR}}}{L_{\odot}} \right) - 2 \log \left( \frac{r_{\text{IR}}}{\text{pc}} \right) \right] \quad (5)$$



**Fig. 5. a)** The  $T_d$  vs.  $L_{\text{IR}}$  diagram for the  $60 \mu\text{m}$  sample. The radius of the circles is the IR radius, assumed to be proportional to the linear radio continuum  $HWHM$  along the major axis. **b)** IR luminosity vs the effective IR area  $\pi r_{\text{IR}}^2$  for two temperature bins. Galaxies with  $28.5 < T_d < 30.5$  K are plotted with open circles and the ones with  $40 < T_d < 41$  K with filled circles. The solid lines corresponds to the empirical correlation given by Eq. (6) for the mean  $T_d$  of the two subsets. We note that the empirical relation does not exactly bisect the low-temperature subsample because of the RBGS surface brightness detection threshold (dashed line, from Wang & Helou 1992) which affect the completeness of the low-temperature subsample.

that can be written as

$$T_d = (23.5 \pm 0.3) \left( \frac{\Sigma_{\text{IR}}}{L_{\odot} \text{pc}^{-2}} \right)^{0.052 \pm 0.002} \text{ K}, \quad (6)$$

where  $T_d$  and  $\Sigma_{\text{IR}}$  are the effective dust temperature and the infrared surface brightness defined in Sect 2.

For the resolved  $170 \mu\text{m}$  sample, the relation is

$$T_d = (22.9 \pm 0.4) \left( \frac{\Sigma_{\text{IR}}}{L_{\odot} \text{pc}^{-2}} \right)^{0.057 \pm 0.004} \text{ K}, \quad (7)$$

which is consistent with the equation obtained for the  $60 \mu\text{m}$  sample.

## 6. Modelling

Two idealized scenarios were considered to interpret the physical processes behind the empirical relation Eq. (6): the dust being distributed in a single shell of radius equal to the observed star-forming radius  $r_{\text{IR}}$  or in molecular clouds optically thin at far-infrared wavelengths.

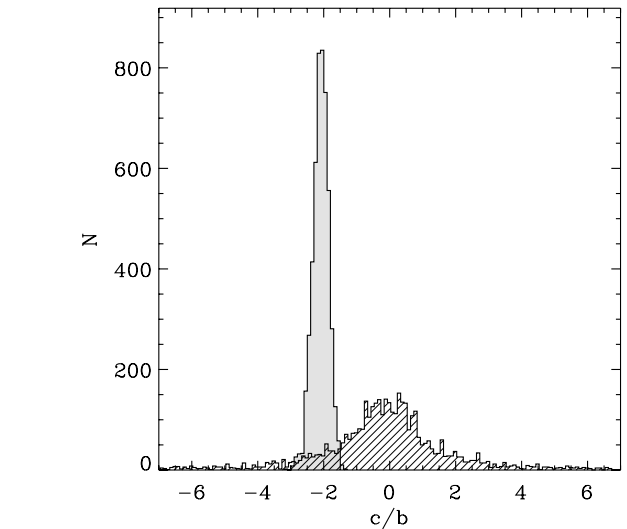
### 6.1. Single dust shell

In this case, we assume that all the dust is distributed in an isothermal shell of radius  $R$  around a point-source starburst. Lehnert & Heckman (1996) have proposed that this model is in agreement with the  $\Sigma_{\text{IR}}-T_d$  relation.

The energy absorbed and emitted by a grain of size  $a$  and of emissivity  $Q_{\text{abs}}(\nu)$  is

$$E_{\text{abs}} = \pi a^2 \int_0^{+\infty} Q_{\text{abs}}(\nu) F_{\nu}(\nu) d\nu \quad (8)$$

$$E_{\text{em}} = 4\pi a^2 \int_0^{+\infty} Q_{\text{abs}}(\nu) \pi B_{\nu}(\nu, T_d) d\nu. \quad (9)$$



**Fig. 6.** Distribution of the values  $c/b$  resulting from the regression fits of the bootstrap samples to the linear form  $\log R(60/100) = a + b \log L_{\text{IR}} / L_{\odot} + c \log r_{\text{IR}} / \text{pc}$ . For the shaded histogram, the real observed values  $R(60/100)$ ,  $L_{\text{IR}}$ , and  $T_d$  of the  $60 \mu\text{m}$  sample have been used whereas in the hatched histogram, the  $R(60/100)$  values have been randomly permuted. The bootstrap estimation of  $c/b$  only converges for the real observed sample, to the value  $-2.09 \pm 0.24$ , which is consistent with  $R(60/100)$  being a function of  $L_{\text{IR}}/r_{\text{IR}}^2$ .

Assuming that the emissivity  $Q_{\text{abs}}(\nu) \simeq 1$  in the UV-optical regime and  $Q_{\text{abs}}(\nu) \simeq Q_{\text{abs}}(\nu_0) (\nu/\nu_0)^{\beta}$  in the infrared regime, Eqs. (8) and (9) yield

$$E_{\text{abs}}/\pi a^2 = \int_0^{+\infty} F_{\nu}(\nu) d\nu \quad (10)$$

$$E_{\text{em}}/\pi a^2 = \frac{8\pi h}{c^2} \left( \frac{kT_d}{h} \right)^{4+\beta} \frac{Q_{\text{abs}}(\nu_0)}{\nu_0^{\beta}} \int_0^{+\infty} \frac{x^{3+\beta}}{e^x - 1} dx \quad (11)$$



where  $\nu_0$  is a reference frequency,  $\beta$  is the dust emissivity index, and  $x = h\nu/kT_d$  in the expanded Planck function.

Assuming that the dust shell is optically thick, the energy radiated by the central starburst is totally reemitted in the infrared and the right-hand part of Eq. (10) becomes

$$E_{\text{abs}}/\pi a^2 = \frac{L_{\text{IR}}}{4\pi R^2} = \frac{1}{4}\Sigma_{\text{IR}}. \quad (12)$$

The right-hand part of Eq. (11) can also be rewritten as

$$E_{\text{em}}/\pi a^2 = \frac{4\sigma_\beta Q_{\text{abs}}(\nu_0)}{\nu_0^\beta} T_d^{4+\beta} \quad \beta > -3, \quad (13)$$

by using the equality (Fikhtengol'ts 1947)

$$\int_0^\infty \frac{x^{k-1}}{e^{ax}-1} dx = \frac{1}{a^k} \Gamma(k) \zeta(k) \quad k > 1, \Re a > 0,$$

where  $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$  is the Gamma function and  $\zeta(z) = \sum_{n=1}^\infty 1/n^z$  is the Riemann's Zeta function, and by setting

$$\sigma_\beta = \frac{2\pi k^{4+\beta}}{c^2 h^{3+\beta}} \Gamma(4+\beta) \zeta(4+\beta), \quad (14)$$

for which  $\sigma_{\beta=0}$  is equal to the Stefan-Boltzmann constant that relates the bolometric luminosity of a blackbody to its temperature.

At the thermal equilibrium,  $E_{\text{abs}} = E_{\text{em}}$ , and the dust temperature is related to the IR surface brightness by

$$T_d^{4+\beta} = \frac{\nu_0^\beta}{16\sigma_\beta Q_{\text{abs}}(\nu_0)} \Sigma_{\text{IR}}. \quad (15)$$

By taking  $\beta = 1.3$  (Sect. 2.1) and the standard value  $Q_{\text{abs}}(125 \mu\text{m}) = 7.5 \times 10^{-4}$  (Hildebrand 1983, cf. reviews by Hughes et al. 1997 and Alton et al. 2004), the numerical relation between  $T_d$  and  $\Sigma_{\text{IR}}$  in the single dust shell model is

$$T_d = 7.6 \left( \frac{\Sigma_{\text{IR}}}{L_\odot \text{pc}^{-2}} \right)^{0.19} \text{K}. \quad (16)$$

It is plotted in Fig. 7 and labelled as (1a). It departs significantly from the observational data.

To check that the difference is not due to the crudeness of the assumed dust model and to compare the work by Lehnert & Heckman (1996), we also used the more realistic dust model by Désert et al. (1990). This dust model is calibrated on solar interstellar medium abundances and includes the stochastic heating of PAHs. Although it assumes an isotropic radiation field, it can be used for the single shell geometry, as long as we input the radiative energy density of the dust shell,  $u_\nu = \Sigma_{\text{IR}}/4c$ . The single shell model with the Désert et al. (1990) dust model and with a heating source scaling as a O5 star is plotted in Fig. 7 and labelled as (1b). It shows a steep relation similar to Eq. (16), which is not in accordance with our samples.

As a result, the geometry itself of the single dust shell model is not satisfactory, unless drastic changes in the dust composition occur along the  $\Sigma_{\text{IR}}$  sequence. The apparent agreement between the Lehnert & Heckman (1996) smaller sample and the single dust shell model is likely explained by the fact that the star-forming sizes were estimated from  $\text{H}\alpha$  maps uncorrected for dust attenuation. Because extinction preferentially affects high compactness regions, their maps likely missed the central nuclei of the most compact starbursts, leading to an overestimation of the star-forming sizes and an underestimation of the infrared surface brightness.

## 6.2. UV-optical-thick & FIR-thin molecular clouds

We assume that the infrared emission is from a disk of radius  $R$  and that the dust giving raise to this emission is isothermal. Several dust configurations could yield an isothermal dust population such as thin shells around young star clusters or dust in cirrus exposed to a uniform interstellar radiation field.

We also assume that every dust grain radiates as a blackbody modified by a  $\lambda^{-\beta}$  emissivity function. In the case in which the medium is transparent in the far-infrared but opaque in the optical-UV, the luminosity  $L_{\text{IR}}$  radiated by the dust is proportional to the total mass of dust  $M_d$  and more specifically (Hildebrand 1983)

$$F_\nu(\nu) = \kappa(\nu) M_d \frac{B_\nu(\nu, T_d)}{D^2}, \quad (17)$$

where  $F_\nu$  is the flux density,  $\kappa(\nu)$  is the absorption mass coefficient assumed to be equal to  $\kappa(\nu_0) (\nu/\nu_0)^\beta$  and  $D$  is the distance. The integration of this relation over the frequencies leads to

$$L_{\text{IR}} = 4\pi D^2 \int_0^\infty F_\nu(\nu) d\nu = 4\sigma_\beta \frac{\kappa(\nu_0)}{\nu_0^\beta} M_d T_d^{4+\beta}, \quad (18)$$

where  $\sigma_\beta$  is the ‘‘generalized’’ Stefan-Boltzmann constant which we introduced in Eq. (14).

Setting the dust-to-gas mass ratio  $\eta_d = M_d/M_{\text{gas}}$ , the total luminosity can be related to the total gas mass  $M_{\text{gas}}$  by

$$L_{\text{IR}} = 4\sigma_\beta \frac{\kappa(\nu_0)}{\nu_0^\beta} \eta_d M_{\text{gas}} T_d^{4+\beta}. \quad (19)$$

The size of the star-forming region is introduced in our analysis through the Schmidt law that non-linearly relates the star formation rate to the gas mass surface density with a power index that reliably departs from unity. This law has been most accurately determined by Kennicutt (1998) as

$$\frac{\Sigma_{\text{SFR}}}{M_\odot \text{yr}^{-1} \text{kpc}^{-2}} = 2.5 \times 10^{-4} \left( \frac{\Sigma_{\text{gas}}}{M_\odot \text{pc}^{-2}} \right)^{1.4}, \quad (20)$$

where  $\Sigma_{\text{gas}}$  is the gas mass surface density inside the radius  $R$ .

Kennicutt (1998) derived the star formation rate from the total infrared luminosity

$$\frac{\text{SFR}}{M_\odot \text{yr}^{-1}} = \gamma \frac{L_{\text{IR}}}{5.8 \times 10^9 L_\odot} \quad (21)$$

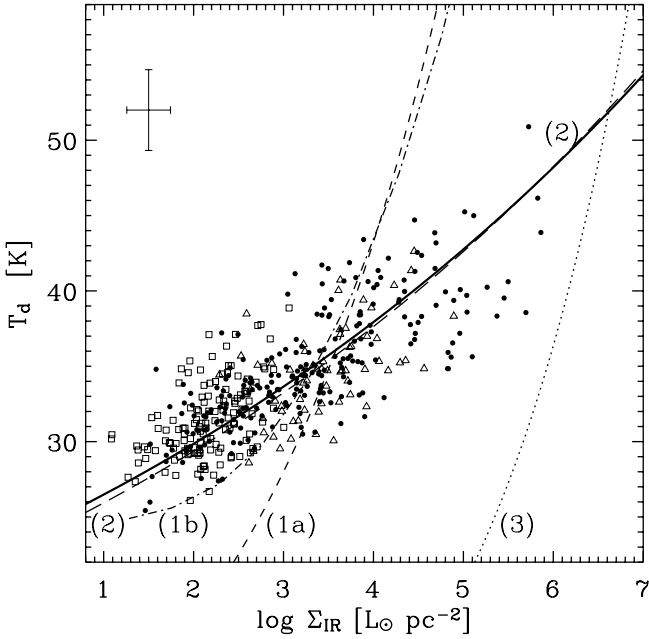
by assuming that the dust absorbs and reprocesses all the intrinsic star light (factor  $\gamma = 1$ ).

Because Eqs. (19) and (21) are linear, both of their sides can be divided by  $\pi R^2$  and expressed in terms of surface densities and surface brightness. By substituting  $\Sigma_{\text{SFR}} = \text{SFR}/\pi R^2$  from Eq. (21) in Eq. (20), we can derive the gas mass surface density as a function of the infrared surface brightness. Then,  $\Sigma_{\text{gas}} = M_{\text{gas}}/\pi R^2$  can be eliminated from Eq. (19) and we obtain the following relation between  $T_d$  and  $\Sigma_{\text{IR}}$

$$T_d^{4+\beta} = 6.27 \times 10^{-5} \frac{\nu_0^\beta}{\sigma_\beta \kappa(\nu_0) \eta_d \gamma^{1/1.4}} \left( \frac{\Sigma_{\text{IR}}}{L_\odot \text{pc}^{-2}} \right)^{0.4/1.4}. \quad (22)$$

Assuming that the interstellar medium is optically thick,  $\gamma = 1$  and by adopting standard values of the parameters involved in our model,  $\kappa(125 \mu\text{m}) = 1.9 \text{ m}^2 \text{ kg}^{-1}$  (Hildebrand 1983),





**Fig. 7.** The effective dust temperature  $T_d$  vs. the IR surface brightness  $\Sigma_{\text{IR}}$  for the  $60\ \mu\text{m}$  sample (filled circles) and the  $170\ \mu\text{m}$  sample (open squares and triangles for the sources with reliable NVSS and FIRST angular sizes respectively). The solid thick line shows the empirical relation Eq. (6). The dashed line (1a) represents the single dust shell model with an analytical dust model (Sect. 6.1, Eq. (16)), and the dot-dashed line (1b) the single dust shell model coupled with the Désert et al. (1990) dust model. The long-dashed line (2) is the model involving the Schmidt law (Sect. 6.2, Eq. (23)) and the dotted line (3) is the expected relation for a blackbody (Eq. (24)). The average uncertainties in  $T_d$  and  $\Sigma_{\text{IR}}$  are shown based on errors of 10 per cent for  $f_{\nu}(60\ \mu\text{m})$ , 15 per cent for  $f_{\nu}(100\ \mu\text{m})$  and 20 per cent for  $r_{\text{IR}}$ .

$\eta_d = 1/350$  (see Sanders et al. 1991; Bendo et al. 2003) and  $\beta = 1.3$ , Eq. (22) gives

$$T_d = (22.9 \pm 0.9) \left( \frac{\Sigma_{\text{IR}}}{L_{\odot} \text{pc}^{-2}} \right)^{0.054 \pm 0.013} \text{ K}. \quad (23)$$

This equation is plotted in Fig. 7 and labelled as (2). It is in very close agreement over 5 orders of magnitude with the empirical relation Eq. (6) obtained from the  $60\ \mu\text{m}$  sample of galaxies and is in accord with the  $170\ \mu\text{m}$  sample, though we should bear in mind that the actual position of the theoretical relation could be translated along the  $T_d$ -axis because of the uncertainties in  $\kappa(\nu_0)$  and  $\eta_d$ .

## 7. Discussion

### 7.1. Selection biases

Sources with  $10^{10} < L_{\text{IR}} < 10^{10.5} L_{\odot}$  are on average colder in the  $170\ \mu\text{m}$  NVSS-resolved subsample ( $\langle T_d \rangle = 30.5\ \text{K}$ ) than in the  $60\ \mu\text{m}$  sample (34.0 K). The difference is not the result of the additional selection criteria on the NVSS sources, because their average effective dust temperature is comparable to the whole  $170\ \mu\text{m}$  sample in this luminosity bin. The temperature difference arises from the wavelength selection that affects the  $L_{\text{IR}}-T_d$  diagram, as discussed in Sect. 4. On the contrary, the  $\Sigma_{\text{IR}}-T_d$  relation is followed by both the  $60\ \mu\text{m}$  and  $170\ \mu\text{m}$  selected samples and we conclude that the latter relation is not sensitive to the selection wavelength, and reflects more fundamental physical processes in play in quiescent and starburst galaxies.

Another selection bias that could affect the  $\Sigma_{\text{IR}}-T_d$  relation is the Malmquist bias involved in the determination of the Tully-Fisher relation for spiral galaxies (Tully & Fisher 1977) and the Fundamental Plane of elliptical galaxies (Dressler et al. 1987; Djorgovski & Davis 1987). This bias would underpopulate galaxies with small physical sizes, which would lead to an underestimation of the effective dust temperature of the most compact galaxies. This effect may be present in the  $170\ \mu\text{m}$  samples for which the angular size is censored and to a lesser extent in the  $60\ \mu\text{m}$  sample. However, out of the 75 IRAS sources observed in Condon et al. (1990, 1996) with an angular resolution higher than or equal to  $1''.8$ , only 9 unresolved sources would have passed the selection criteria of the  $60\ \mu\text{m}$  sample described in Sect. 3.1.

Our samples are selected at infrared wavelengths and the  $\Sigma_{\text{IR}}-T_d$  relation may not stand for galaxies fainter in the infrared or with a low metallicity. However, it is unclear whether we should expect higher or lower dust temperatures for these types of galaxies because two factors may be in competition. On one hand, the calibration of the SFR-to- $L_{\text{IR}}$  ratio in Eq. (21) assumes an optically thick dust model. The stellar emission is strongly attenuated in the galaxies of our samples, as shown by the IR to B-band luminosity ratio in Fig. 2g and this assumption is justified for our samples. However, galaxies for which only a fraction of the intrinsic young stellar emission is attenuated by the dust would have higher SFR-to- $L_{\text{IR}}$  ratios ( $\gamma > 1$ ) which would give in Eq. (22) lower dust temperatures for a given IR surface brightness. On the other hand, for example, Wilson et al. (1991) found that the SFR estimated by the IR luminosity was greater than the one estimated by the (extinction-corrected)  $H_{\alpha}$  emission line in the coolest region of the spiral galaxy M 33 and attributed this excess to the presence of interstellar cirrus (Helou 1986). They can represent a non-negligible fraction (up to 50–70% or more, Lonsdale-Persson & Helou 1987; Bell 2003) of the total IR emission in quiescent galaxies. An increase of the interstellar cirrus contribution would decrease the SFR-to- $L_{\text{IR}}$  ratio ( $\gamma < 1$ ) that would in turn increase the dust temperature for a given IR surface brightness. However, it should be noted that the most quiescent galaxies in our samples do not depart from the  $\Sigma_{\text{IR}}-T_d$  relation so it is possible that the two factors compensate themselves or have second order effects.

It should also be noted that the dust in this model is in thermal equilibrium and as a consequence, the stochastic heating of small dust grains is not taken into account. However, with our choice of observables, this fact is mitigated by the adopted definition of  $L_{\text{IR}}$  (Sect. 2.2) which also discards the mid-IR excess emission expected from the smaller dust grains.

### 7.2. Emissivity index dependence

The modelled  $\Sigma_{\text{IR}}-T_d$  relation (Sect. 6.2) has a weak dependence on the emissivity index  $\beta$  as shown in table 3 by the modest variation of the scaling factor  $a$  and the power-law index  $b$  given by the relation  $T_d = a \Sigma_{\text{IR}}^b$ . The modelled values of  $a$  and  $b$  have been calculated with the same values of the absorption mass coefficient  $\kappa(\nu_0)$  and dust-to-gas ratio  $\eta_d$  as in Sect. 6.2 ( $\beta = 1.3$ ). Because of the uncertainties associated with these two parameters, the comparison between the empirical and modelled scaling factors  $a$  is not insightful, as already noted. More noteworthy, the empirical and modelled power-law indices  $b$  do not depart from each other as  $\beta$  varies, which makes the agreement of the model with the observations not sensitive to our initial choice of emissivity index.

**Table 3.** Dependence of the  $\Sigma_{\text{IR}}-T_{\text{d}}$  relation on the emissivity index  $\beta$ . The effective dust temperature is given by  $T_{\text{d}} = a \Sigma_{\text{IR}}^b$  with  $\Sigma_{\text{IR}}$  being in unit of  $L_{\odot} \text{pc}^{-2}$ . The empirical relation is fitted to the  $60 \mu\text{m}$  sample. The model is described in Sect. 6.2 and assumes an absorption mass coefficient  $\kappa(125 \mu\text{m}) = 1.9 \text{ m}^2 \text{ kg}^{-1}$  and a constant dust-to-gas mass ratio  $\eta_{\text{d}} = 1/350$ .

$\beta$	Observation		Model	
	$a$	$b$	$a$	$b$
1	24.32	0.0549	22.77	0.0571
1.5	22.96	0.0503	22.94	0.0519
2	21.68	0.0466	22.88	0.0476

### 7.3. The $L_{\text{IR}}-T_{\text{d}}$ degeneracy

With conservative errors of 10 and 15 per cent for the *IRAS* flux densities at 60 and 100  $\mu\text{m}$ , the statistical standard deviation of the effective dust temperature of the 60  $\mu\text{m}$  dataset is expected to be 2.8 K. It is compatible with the sample standard deviation, which is lower than 3.2 K along the  $\Sigma_{\text{IR}}-T_{\text{d}}$  sequence. It implies that the introduction of the size parameter has mostly disentangled the degeneracy of the  $L_{\text{IR}}-T_{\text{d}}$  diagram down to current observational precision. The FIR all-sky survey by the satellite *Akari* will be able to address further this issue.

### 7.4. A starburst temperature limit?

One can wonder what part of the  $\Sigma_{\text{IR}}-T_{\text{d}}$  diagram would be populated by ultra-compact starbursts not resolved or too faint to be included in our samples and for which the assumption of FIR-thin molecular clouds may be incorrect. As the distribution of IR emission becomes more compact, the FIR opacity would increase until the source becomes a blackbody, for which the IR surface brightness is related to the temperature by  $T_{\text{d}} = (\Sigma_{\text{IR}}/4\sigma_{\beta=0})^{1/4}$ , or numerically by

$$T_{\text{d}} = 1.15 \left( \frac{\Sigma_{\text{IR}}}{L_{\odot} \text{pc}^{-2}} \right)^{0.25} \text{ K.} \quad (24)$$

Ultra-compact starbursts would lay in Fig. 7 on the left-hand side of the steep Eq. (24) and on the upper side of Eq. (23). In this scenario, the effective dust temperature would not be constrained. However, the FIR-opacity of the most active starbursts is still a matter of debate. Another scenario proposed by Klaas et al. (2001) for ultra-luminous galaxies driven by star-formation, is that such galaxies are still mostly FIR-thin and as a consequence, they would still follow the relation given by Eq. (23) until they reach the empirical starburst intensity limit by Meurer et al. (1997) of  $2.0 \times 10^5 L_{\odot} \text{pc}^{-2}$  (with a factor of 3 uncertainty). With these assumptions, the effective temperature would then be limited to around 44 K for 90% or more starbursts.

## 8. Conclusions

We constructed two well-defined local datasets selected at 60  $\mu\text{m}$  and 170  $\mu\text{m}$ , which are made of 430 IR-bright, non-AGN galaxies with reliable radio continuum sizes. We used them to investigate the relation between three global parameters, namely the infrared luminosity  $L_{\text{IR}}$ , the effective dust temperature  $T_{\text{d}}$  and the size of the star-forming region  $r_{\text{IR}}$ . We show that

1. The dispersion in the  $L_{\text{IR}}-T_{\text{d}}$  diagram can be explained by introducing the size of the star-forming region.

2. Infrared bright non-AGN galaxies form a plane in the  $(L_{\text{IR}}, T_{\text{d}}, r_{\text{IR}})$  space akin to the fundamental planes of the spiral and elliptical galaxies.
3. The effective dust temperature is related to  $L_{\text{IR}}/r_{\text{IR}}^2$ , i.e. the IR surface brightness, by a power-law over 5 orders of magnitude.
4. Unlike the  $L_{\text{IR}}-T_{\text{d}}$  relation, the  $\Sigma_{\text{IR}}-T_{\text{d}}$  relation does not depend on the IR wavelength used to select or detect galaxy samples.
5. The empirical relation is in agreement with a simplified model made of isothermal molecular clouds which are opaque in the optical and transparent in the FIR and for which we assumed a constant emissivity index, gas-to-dust ratio and mass absorption coefficient.
6. The model for which the dust is distributed in a single shell around the central starburst is ruled out.
7. Because  $T_{\text{d}}$  also traces the SFR per unit of gas mass, the SFR per unit of gas mass correlates with the SFR per unit area.
8. The infrared compactness turns out to be a parameter able to describe the smooth sequence ranging from quiescent to starburst galaxies in which the gas surface density, the effective dust temperature, the SFR per unit of gas mass and the SFR per unit area increase together.

Assuming that the relation holds for distant galaxies, they may be significant, since the hierarchical framework of structure formation predicts a decrease of sizes with redshift. It would induce an evolution of galaxy colors, which may statistically affect the derivation of the cosmic star formation rate from infrared galaxy number counts. Such a study will be carried on a subsequent paper.

The unprecedented angular far-infrared resolution of ESA's *HERSCHEL* space observatory will allow us to further probe the infrared compactness-temperature relation. In a more distant future, high redshift galaxies will be spatially resolved by missions included in the ESA Cosmic Vision Programme such as the Far InfraRed Mission (*FIRM*) or in the NASA space science roadmap such as: the Single Aperture Far-IR telescope (*SAFIR*), the Space IR Interferometric Telescope (*SPiRiT*) and the Submillimeter Probe of the Evolution of Cosmic Structures (*SPECS*).

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# Online Material

**Table 4.** Global properties of the 170  $\mu\text{m}$  sample resolved in the NVSS radio continuum catalog.

Name	PGC	RA (2000)	Dec (2000)	Type	$D$	$\log L_{\text{IR}}$	$\log L_{\text{IR}}/\nu L_{\text{B}}$	$\log r_{\text{IR}}$	$\log \Sigma_{\text{IR}}$	$T_{\text{d}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NGC 7817	279	00 03 58.90	+20 45 08.4	Sbc	33.9	10.27	0.37	3.77	1.94	29.1
UGC 00148	1051	00 15 51.26	+16 05 23.4	Sbc	62	10.36	0.44	3.64	2.29	32.8
MCG -01-01-064	1109	00 16 50.87	-05 16 06.1	SBa	56.8	10.29	0.89	3.55	2.39	31.6
MCG +08-01-041	1414	00 22 01.22	+49 08 00.1	Sc	77.7	10.44	0.63	3.59	2.46	32.7
UGC 00256	1658	00 26 56.53	+50 01 50.4	Sbc	78.1	10.61	1.00	3.68	2.45	31.2
IC 1562	2308	00 38 33.95	-24 16 26.8	SBc	52.6	10.00	0.14	3.71	1.78	29.6
NGC 0200	2387	00 39 34.85	+02 53 14.7	Sbc	74.7	10.42	0.13	3.77	2.08	30.0
NGC 0214	2479	00 41 28.01	+25 29 57.6	SABc	67.1	10.51	0.10	3.60	2.51	29.0
NGC 0245	2691	00 46 05.39	-01 43 24.2	Sb	58.2	10.56	0.19	3.65	2.46	32.5
UGC 00540	3108	00 52 58.29	+29 01 56.5	Sb	73.8	10.28	0.29	3.65	2.18	33.9
MCG -05-03-011	3159	00 53 43.45	-27 02 59.3	Sc	78.2	10.40	0.62	3.63	2.35	32.4
NGC 0418	4189	01 10 35.61	-30 13 16.6	Sc	80.2	10.48	0.01	3.89	1.90	30.9
IC 1671	4724	01 19 02.34	-17 03 37.5	Sb	84.8	10.81	0.75	3.63	2.75	37.8
NGC 0470	4777	01 19 44.83	+03 24 35.8	Sb	31.1	10.19	0.30	3.27	2.85	36.8
NGC 0491	4914	01 21 20.43	-34 03 47.8	SBb	53.3	10.45	0.36	3.51	2.63	29.3
MCG -07-04-004	5278	01 25 28.48	-38 16 02.4	S0-a	86.6	10.12	0.17	3.98	1.37	29.7
MCG -04-06-009	8223	02 09 18.08	-23 24 54.2	Sbc	74.7	10.78	0.49	3.64	2.71	29.7
UGC 02028	9729	02 33 18.19	+22 23 37.8	Sc	79.2	10.38	0.41	3.89	1.80	27.8
NGC 1070	10309	02 43 22.29	+04 58 06.4	Sb	58.3	10.27	-0.14	3.72	2.05	27.8
UGC 02198	10319	02 43 32.65	+31 47 24.0	Scd	69.4	10.32	0.96	3.76	2.01	29.6
NGC 1077 NED02	10468	02 46 00.57	+40 05 24.6	Sb	133	10.67	0.22	3.88	2.11	30.5
NGC 1094	10559	02 47 27.81	-00 17 06.5	SABa	92.5	10.53	0.15	3.89	1.96	29.2
NGC 1103	10597	02 48 05.99	-13 57 33.3	SBb	57.7	10.24	0.23	3.78	1.88	30.9
UGC 02380	11011	02 55 11.09	+51 54 25.7	Sb	69.7	10.10		3.86	1.58	29.4
UGC 02409	11134	02 56 44.98	+50 35 43.5	Sbc	58.8	10.53	1.40	3.62	2.49	32.9
MRK 0602	11336	02 59 50.60	+02 46 16.7	SBbc	36.9	10.03	0.51	3.26	2.71	37.7
UGC 02801	13410	03 38 19.79	+41 17 34.0	Sc	73.8	10.23	0.96	3.81	1.80	29.9
IRAS F03379+6754	165371	03 42 46.70	+68 04 02.7	Sc	161	11.00	1.37	3.89	2.42	35.0
UGC 03028	15047	04 24 35.23	+33 52 29.8	Sb	80.5	10.68	1.19	3.85	2.19	29.4
UGC 03089	15533	04 33 54.00	+16 54 43.5	Sbc	66.4	10.09	0.66	3.61	2.07	29.2
NGC 1620	15638	04 36 37.34	-00 08 36.9	SABc	49.3	10.15	-0.02	3.84	1.68	28.0
IC 0391	16402	04 57 21.18	+78 11 25.3	Sc	24.8	9.90	0.38	3.32	2.47	37.1
NGC 1843	16949	05 14 06.14	-10 37 36.6	SABc	35	9.94	0.24	3.62	1.90	30.5
IRAS 05175+0547	17126	05 20 12.59	+05 50 15.2	Sb	124	10.77	0.77	3.80	2.38	34.6
NGC 2076	17804	05 46 47.46	-16 46 57.5	S0-a	29.5	10.30	1.00	3.42	2.66	29.5
UGC 03340	17839	05 47 27.36	+79 38 09.1	Sab	68.6	10.61	0.92	3.61	2.60	34.2
ESO 055415-1941.8	18115	05 56 25.18	-19 41 31.0	Sab	37.3	9.93	0.59	3.28	2.58	33.3
MCG -03-16-006	18220	06 00 20.49	-16 10 00.0	Sa	92.6	10.66	0.79	3.67	2.52	33.1
IC 0454	19725	06 51 06.30	+12 55 19.6	SBab	56.8	10.32		3.75	2.01	29.2
UGC 03830	20894	07 23 30.55	+02 36 56.8	SBcd	20	9.33	0.72	3.22	2.09	33.0
NGC 2446	21860	07 48 39.26	+54 36 43.0	Sb	85.2	10.54	0.17	3.82	2.11	28.4
NGC 2958	27620	09 40 41.61	+11 53 18.4	SABb	97.5	10.56	0.10	3.76	2.24	31.4
NGC 3218	30323	10 21 49.00	+74 10 36.8	SBbc	49.4	10.41	0.16	3.65	2.30	29.6
MCG -06-23-029	30716	10 27 02.50	-36 13 41.5	Sbc	43.6	10.06	0.62	3.63	2.01	31.2
MCG -05-25-031	31677	10 39 14.89	-30 17 52.1	Sbc	53.1	10.20	0.36	3.52	2.35	30.8
NGC 3430	32614	10 52 11.41	+32 57 01.5	Sc	28.7	9.94	-0.04	3.72	1.70	30.8
ARP 062	37282	11 53 39.95	+43 27 39.6	Sab	89.3	10.67	0.59	3.88	2.12	33.7
NGC 4125A	38212	12 04 33.92	+64 26 12.2	Sa	26.6	9.55	0.08	3.32	2.12	32.6
NGC 4205	39143	12 14 55.33	+63 46 55.7	Sbc	26.2	9.55	0.16	3.36	2.04	32.1
NGC 4294	39925	12 21 17.81	+11 30 38.4	SBc	18	9.34	-0.17	3.35	1.84	33.9
NGC 4299	39968	12 21 40.52	+11 30 10.8	SABd	18	9.30	-0.07	3.28	1.94	34.6
NGC 4383	40516	12 25 25.53	+16 28 12.1	Sa	15.3	9.61	0.38	2.88	3.06	38.9
NGC 4402	40644	12 26 07.57	+13 06 46.1	Sb	15.3	9.66	0.53	3.28	2.30	28.5
IRAS F12334+6414	41961	12 35 42.04	+63 58 25.5	S?	163	11.04	0.64	3.98	2.28	31.2
IC 3587	42083	12 36 48.35	+27 32 55.0	Sc	110	10.33	0.63	4.22	1.09	30.5
MCG -03-33-003	42954	12 44 51.84	-20 25 35.4	Sc	91.7	10.77	0.38	3.69	2.59	33.2
NGC 4670	42987	12 45 17.15	+27 07 31.9	S0-a	11.8	8.87	0.05	2.95	2.17	37.1
NGC 4701	43331	12 49 11.55	+03 23 19.5	Sc	22	9.56	0.06	3.37	2.03	31.5
NGC 4868	44557	12 59 08.90	+37 18 36.9	Sab	71.8	10.71	0.22	3.57	2.77	31.3
NGC 4900	44797	13 00 39.15	+02 30 05.3	SBc	15.4	9.58	0.04	3.31	2.17	32.0
NGC 4981	45574	13 08 48.74	-06 46 39.3	Sbc	29.9	10.02	-0.04	3.72	1.77	31.4
NGC 5012	45795	13 11 37.04	+22 54 55.5	Sc	43.6	10.23	0.12	3.77	1.90	30.1
MCG -05-31-039	45901	13 12 55.44	-32 41 23.5	SBcd	35.9	9.65	-0.03	3.88	1.09	30.2
NGC 5056	46180	13 16 12.33	+30 57 01.0	Sc	85	10.37	0.06	3.76	2.05	32.0
NGC 5113	46589	13 20 52.79	+57 38 29.5	Sbc	36.5	9.51	-0.24	3.42	1.86	34.8
NGC 5149	47011	13 26 09.17	+35 56 04.0	SBbc	86.2	10.90	0.53	3.66	2.79	34.8
NGC 5301	48816	13 46 24.61	+46 06 26.7	SBc	29.8	9.88	0.33	3.86	1.35	27.3
NGC 5303A	48917	13 47 44.96	+38 18 16.2	Sc	26.9	9.75	0.02	3.30	2.36	33.5
NGC 5351	49359	13 53 27.72	+37 54 54.0	SBb	57	10.12	-0.09	3.92	1.49	29.5
NGC 5372	49451	13 54 45.98	+58 39 59.0	S?	30.8	9.73	0.22	3.22	2.49	34.4

Table 4. continued.

Name	PGC	RA (2000)	Dec (2000)	Type	$D$	$\log L_{\text{IR}}$	$\log L_{\text{IR}}/\nu L_B$	$\log r_{\text{IR}}$	$\log \Sigma_{\text{IR}}$	$T_d$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
IC 4367	50266	14 05 36.57	-39 12 12.2	SABc	59	10.36	0.15	3.74	2.08	28.2
NGC 5480	50312	14 06 21.52	+50 43 30.0	Sc	34.4	10.13	0.24	3.37	2.58	30.1
NGC 5504	50718	14 12 15.83	+15 50 31.2	Sbc	79.5	10.39	0.16	3.72	2.14	30.9
NGC 5526 NED02	50832	14 13 53.73	+57 46 16.7	Sbc	34.8	9.85	0.73	3.26	2.54	32.2
NGC 5522	50889	14 14 50.36	+15 08 48.1	Sb	69.8	10.40	0.35	3.68	2.24	34.0
NGC 5533	50973	14 16 07.69	+35 20 37.5	Sab	60.7	10.18	-0.25	3.71	1.96	26.1
IC 0991	51059	14 17 48.59	-13 52 22.4	Sbc	68.9	10.35	0.25	3.88	1.79	28.8
NGC 5592	51428	14 23 55.06	-28 41 17.3	Sbc	62.8	10.58	0.46	3.58	2.62	30.5
NGC 5614	51439	14 24 07.61	+34 51 32.1	Sab	61	10.30	-0.18	3.66	2.17	26.7
NGC 5604	51471	14 24 42.80	-03 12 43.7	Sa	42.8	10.18	0.41	3.46	2.45	31.2
NGC 5637	51736	14 28 59.64	+23 11 29.5	Sc	80.1	10.41	0.56	3.64	2.33	32.7
MCG -04-34-019	51902	14 31 32.15	-25 23 12.1	Sc	38.3	9.77	0.44	3.39	2.19	30.2
IC 4468	52324	14 38 26.79	-22 22 03.0	Sbc	37	9.71	0.22	3.72	1.47	28.9
IC 1048	52564	14 42 57.88	+04 53 24.6	Sbc	29.7	9.70	0.35	3.50	1.90	29.4
UGC 09509 NOTES01	52726	14 46 01.81	+08 29 46.0		156	10.83	1.01	3.91	2.21	35.6
NGC 5757	52839	14 47 46.37	-19 04 42.8	Sb	36.3	10.31	0.57	3.37	2.78	35.0
NGC 5875	54095	15 09 13.21	+52 31 42.0	Sb	56.4	10.40	0.22	3.74	2.12	28.4
NGC 5908	54522	15 16 43.23	+55 24 33.5	Sb	53.3	10.65	0.39	3.86	2.13	28.2
NGC 5961	55515	15 35 16.25	+30 51 50.9	Sb	30.7	9.52	0.41	3.32	2.08	34.8
ESO 154918-3842.1	56278	15 52 36.60	-38 51 00.7	Sbc	65.7	10.61	1.46	3.58	2.65	31.8
IC 1151	56537	15 58 32.31	+17 26 29.7	Sbc	36.2	9.59	-0.08	3.59	1.61	30.9
UGC 10123	56570	15 59 02.75	+51 18 16.1	Sab	60	10.28	0.68	3.60	2.28	29.3
IC 1210	57589	16 14 30.14	+62 32 12.0	Sab	48	9.93	0.63	3.50	2.14	31.2
NGC 6168	58423	16 31 21.41	+20 11 04.8	Sd	41.1	9.88	0.47	3.56	1.97	32.2
IC 1228	58804	16 42 06.50	+65 35 08.0	Sab	116	11.07	0.72	3.79	2.69	33.9
IRAS F16463-0642	90256	16 49 01.59	-06 47 28.0	S?	94.1	10.67		3.78	2.32	34.5
NGC 6246A	59090	16 50 13.98	+55 23 04.8	Sc	81.6	10.36	0.23	4.09	1.39	28.6
MCG -01-43-002	59133	16 51 32.32	-03 05 46.9	Sbc	107	10.74	0.84	4.13	1.69	30.1
NGC 6368	60315	17 27 11.55	+11 32 32.9	Sb	44.1	10.10	0.18	3.62	2.06	29.1
NGC 6372	60330	17 27 31.86	+26 28 30.6	Sbc	73.3	10.42	0.23	3.77	2.08	29.9
UGC 10885	60403	17 30 08.34	+35 21 59.3	Sb	122	10.75	0.66	3.90	2.15	30.2
NGC 6389	60466	17 32 39.78	+16 24 06.2	Sbc	49.3	10.07	-0.11	3.91	1.45	29.7
UGC 10976	60833	17 46 27.83	+30 42 17.0	SBbc	75.9	10.45		3.71	2.24	32.0
NGC 6478	60896	17 48 38.33	+51 09 26.2	Sc	104	10.79	0.34	3.89	2.22	27.8
IRAS F18023+2311	165751	18 04 26.08	+23 11 20.5	S?	161	11.03		3.93	2.37	36.3
MCG +02-46-012	61658	18 15 58.28	+13 47 07.1	Sc	47.4	9.93	0.47	3.52	2.09	31.2
IRAS 18216+5117	61797	18 22 50.70	+51 19 09.5	S?	126	10.76	0.60	3.82	2.33	32.1
NGC 6632	61849	18 25 03.09	+27 32 07.3	Sbc	73.4	10.50	0.02	3.98	1.74	29.9
NGC 6640	61913	18 28 08.24	+34 18 09.7	Sc	104	10.40	0.29	4.00	1.60	31.7
NGC 6678	61972	18 30 39.80	+67 59 13.3	SABa	42.6	10.09	0.26	3.34	2.62	32.7
NGC 6677	62035	18 33 36.12	+67 06 38.4	Sbc	102	10.86	0.37	3.75	2.57	33.4
NGC 6700	62376	18 46 04.42	+32 16 46.5	SBc	71	10.09	0.01	3.95	1.38	29.4
UGC 11379	62593	18 56 43.96	+25 14 13.9	Sc	68	10.06	0.48	3.65	1.96	35.4
UGC 11404	62781	19 07 03.79	+29 00 23.1	Sbc	61	10.47	0.41	3.85	1.97	30.2
UGC 11428	63084	19 20 28.55	+30 49 31.6	SABc	61.5	10.27	0.45	3.70	2.08	30.7
NGC 6796	63121	19 21 30.82	+61 08 41.5	Sbc	37.1	10.23	0.56	3.51	2.42	28.9
NGC 6801	63229	19 27 35.80	+54 22 22.5	Sc	67.5	10.32	0.48	3.90	1.73	29.9
UGC 11453	63311	19 31 08.05	+54 06 07.8	Sb	60.7	10.53	0.20	3.65	2.42	29.0
IC 1303	63328	19 31 30.06	+35 52 35.8	Sc	69.1	10.23	0.54	3.80	1.83	30.8
NGC 6824	63575	19 43 40.65	+56 06 33.9	Sab	49	10.62	0.48	3.41	3.00	30.9
NGC 6911	64485	20 19 38.32	+66 43 42.2	SBb	41.4	10.29	1.05	3.54	2.40	30.9
NGC 6898	64517	20 21 08.01	-12 21 32.3	SBA	83.2	10.59		3.68	2.44	31.9
NGC 6916	64600	20 23 33.06	+58 20 38.6	SBbc	49.8	10.30	0.96	3.73	2.04	29.2
NGC 6928	64932	20 32 50.21	+09 55 35.2	SBab	70.8	10.50	0.29	3.82	2.07	29.5
NGC 6949	65010	20 35 06.94	+64 48 10.2	Sc	45	9.93	0.50	3.65	1.84	29.0
IRAS 20340+5124	166684	20 35 28.85	+51 35 27.4	Sc	50.4	10.51	1.62	3.41	2.89	32.2
UGC 11599	65060	20 36 33.82	+11 29 40.9	Sb	67.2	10.37	0.25	4.15	1.27	27.6
UGC 11723	66579	21 20 17.50	-01 41 03.5	Sb	72.4	10.52	0.77	3.74	2.25	29.8
NGC 7218	68199	22 10 11.71	-16 39 39.6	Sc	23.7	9.85	0.13	3.44	2.16	33.0
MCG -04-52-024	68313	22 13 10.45	-22 26 42.2	Sab	75.6	10.40	0.44	3.61	2.39	35.0
IRAS 22287+6137	87389	22 30 30.38	+61 52 49.9	Sc	55.1	10.72	2.75	3.51	2.89	34.8
NGC 7347	69443	22 39 56.16	+11 01 39.2	Sc	34.3	9.71	0.46	3.43	2.06	31.0
NGC 7741	72237	23 43 54.37	+26 04 32.1	Sbc	13.2	9.19	-0.27	3.43	1.54	31.6
NGC 7755	72444	23 47 51.77	-30 31 19.5	Sc	39.9	10.16	0.02	3.71	1.93	29.6

Columns: (5) Morphological type from HYPERLEDA (6) distance in Mpc; (7) infrared luminosity in  $L_{\odot}$  derived from the 60 and 100  $\mu\text{m}$  IRAS flux densities, by assuming a modified blackbody of emissivity index  $\beta = 1.3$ ; (8) ratio of the IR to  $B$ -band luminosities; (9) IR physical radius in pc; (10) IR surface brightness in  $L_{\odot} \text{pc}^{-2}$ ; (11) effective dust temperature in K.

**Table 5.** Global properties of the 170  $\mu\text{m}$  sample resolved in the FIRST radio continuum catalog.

Name	PGC	RA (2000)	Dec (2000)	Type	$D$	$\log L_{\text{IR}}$	$\log L_{\text{IR}}/\nu L_{\text{B}}$	$\log r_{\text{IR}}$	$\log \Sigma_{\text{IR}}$	$T_{\text{d}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
MCG -02-02-005	1404	00 21 51.12	-09 29 32.0	S0-a	90.1	10.16	0.48	2.71	3.93	37.0
MCG -02-03-066	3662	01 01 19.43	-09 50 43.4	Sb	65.3	10.22	0.65	2.59	4.23	40.4
IRAS F01222+0038	5219	01 24 48.93	+00 54 36.4	S0-a	144	10.79	0.71	3.38	3.24	34.8
UGC 02403	11075	02 55 57.27	+00 41 33.0	SBa	53.8	10.68	1.15	2.49	4.89	38.3
IRAS F09489+2746	139220	09 51 46.50	+27 32 45.5	S?	147	10.63	1.08	3.29	3.24	36.0
MRK 0126	28460	09 52 36.83	+52 13 18.4	Sc	176	10.76		3.67	2.62	28.6
IRAS F10134+2230	1666567	10 16 11.67	+22 15 35.3	S?	296	11.28	0.98	3.21	4.06	35.3
UGC 05605	30393	10 22 46.48	+48 38 13.7	Sb	225	10.96	0.48	3.12	3.92	32.3
MCG +08-21-055	35717	11 33 57.59	+45 16 00.0	Sab	150	10.55	0.56	3.07	3.62	32.6
MCG +08-21-093	36396	11 43 04.49	+48 23 56.0	Sab	65.4	10.03	0.37	3.28	2.67	29.4
IRAS F12207+6329	40158	12 23 05.24	+63 13 21.2	S?	268	11.52	0.91	3.15	4.42	41.4
IC 3627	139990	12 39 32.02	+27 29 50.5	S?	257	11.07	1.02	3.29	3.69	37.5
UGC 08168	45117	13 03 41.11	+51 29 45.6		178	10.77		3.13	3.72	34.0
NGC 5104	46633	13 21 23.11	+00 20 33.5	SBa	82.4	11.05	1.05	2.84	4.56	34.8
IRAS 13232+1731	2816875	13 25 43.88	+17 15 53.0	S?	360	11.46	0.87	3.75	3.17	31.4
2MASX J13465224+1741550	48852	13 46 52.24	+17 41 54.8	Sc	121	10.39	0.24	3.48	2.63	33.5
IRAS F13543+5846	84079	13 56 00.87	+58 31 47.3		181	10.95	1.12	3.25	3.65	34.7
MCG +06-31-036	49754	13 58 41.85	+35 05 16.3	Sab	157	11.26	1.20	3.15	4.16	34.7
UGC 08991	50169	14 04 35.96	+15 28 21.7	S?	117	10.31	0.22	3.14	3.22	36.5
NGC 5472	50345	14 06 55.03	-05 27 37.9	Sab	44.8	9.88	0.57	2.83	3.42	32.5
2MASX J14080087+3613283	2077016	14 08 00.88	+36 13 28.3	S?	271	10.80	0.96	3.86	2.29	34.4
NGC 5520	50728	14 12 22.78	+50 20 54.4	Sb	33.1	9.86	0.14	2.97	3.11	31.3
IRAS F14105+0357	50775	14 13 06.91	+03 42 59.1	S?	114	10.61	0.81	3.24	3.33	35.0
IC 4405	51167	14 19 16.55	+26 17 54.8	Sab	166	10.98	0.45	3.47	3.23	32.1
IRAS F14228+5351	84158	14 24 34.43	+53 38 23.9	S?	138	10.26		3.34	2.77	31.5
NGC 5637	51736	14 28 59.64	+23 11 29.5	Sc	80.1	10.41	0.56	3.35	2.91	32.7
MCG +06-32-070	52138	14 35 18.42	+35 07 07.7	S?	129	11.07		3.60	3.07	34.8
IRAS F14490+5154	52990	14 50 41.24	+51 42 15.7	Sbc	119	10.58	0.86	3.18	3.42	34.8
IRAS F14501+3823	84327	14 52 05.70	+38 10 59.4	S?	147	10.68		3.20	3.49	34.7
IRAS F15017+2417	53766	15 04 00.77	+24 06 17.6		315	11.78		3.27	4.45	42.6
IRAS F15097-0248	54279	15 12 23.14	-02 59 57.9	S?	163	10.69	0.81	3.13	3.63	40.7
MCG +08-28-025	55029	15 24 51.04	+50 18 54.3	Sab	170	10.66	0.54	3.39	3.08	30.2
IRAS F15305+4917	84665	15 32 07.80	+49 07 29.4	S?	114	10.73		3.23	3.48	33.7
IRAS 15313+5802	55361	15 32 31.70	+57 52 58.9	S?	182	10.84	0.44	3.22	3.61	40.0
IC 4581	55893	15 44 01.47	+28 16 36.9	Sc	151	10.65	0.43	3.11	3.63	37.1
UGC 10030	56025	15 47 00.41	-00 59 07.3	Sab	133	10.66	0.50	3.15	3.56	30.1
IRAS F15538+5218	56381	15 55 10.89	+52 10 06.5	S?	169	10.88	0.48	3.61	2.87	35.2
MRK 1101	56442	15 56 36.42	+41 52 50.4	S?	157	11.03	0.65	3.24	3.75	36.3
IRAS 15557+4957	2816987	15 57 14.00	+49 49 15.4	S?	191	10.75	0.76	3.11	3.74	36.3
MRK 0694	56760	16 02 01.78	+16 26 07.2	E-SO	137	10.47	0.52	2.99	3.69	34.7
IRAS F16022+2008	1613262	16 04 26.68	+20 00 32.5	S?	151	10.44	0.76	3.19	3.26	34.0
UGC 10325 NED01	93134	16 17 30.61	+46 05 30.4	Sb	88.6	10.55		3.39	2.98	32.3
NGC 6113	57807	16 19 10.58	+14 08 01.1	S0-a	134	10.77	0.39	3.51	2.96	29.5
NGC 6120	57842	16 19 48.10	+37 46 28.4	Sd	139	11.28	0.72	3.43	3.63	34.6
IRAS F16192+3958	2156824	16 20 55.81	+39 51 39.7	S?	130	10.47	0.87	3.54	2.59	38.5
MCG +09-27-020	57903	16 21 17.74	+51 33 25.4	Sc	136	10.73	0.88	3.58	2.78	30.6
MCG +09-27-021	57907	16 21 25.86	+56 00 34.0	S?	136	10.57	0.78	3.20	3.36	30.5
MCG +08-30-009	57940	16 22 17.83	+50 22 19.0	Sb	259	11.45	0.89	3.15	4.36	35.4
MCG +07-34-018	58046	16 24 37.10	+39 07 40.0	Sb	158	11.04		2.97	4.30	35.2
NGC 6150B	58100	16 25 44.47	+40 28 32.4	Sab	144	10.61	0.44	3.46	2.89	30.3
IRAS 16369+3721	84761	16 38 43.15	+37 15 18.0	S?	138	10.59		2.91	3.98	38.9
MCG +09-27-065	58801	16 42 04.48	+54 41 22.3	SBab	143	10.63	0.86	2.97	3.89	39.4
NGC 6247	59023	16 48 20.25	+62 58 35.0	S?	70.2	10.72	0.39	3.27	3.37	34.8
MCG +10-24-064	59060	16 49 27.83	+58 53 54.9	S?	78.9	10.12	0.50	2.79	3.74	33.1
IRAS F16530+5033	59232	16 54 19.55	+50 28 30.6	S?	47.4	9.94	0.74	2.96	3.22	33.9
IRAS F17072+3627	165719	17 08 58.64	+36 23 56.7	S?	124	10.66		2.91	4.04	36.8
MCG +10-24-102	59767	17 11 00.57	+56 56 08.2	S?	132	10.57	0.47	3.53	2.71	35.1
IC 1249	59919	17 14 54.98	+35 31 14.2	S?	169	10.90	0.32	3.56	2.98	32.0
UGC 10812	60074	17 19 28.77	+40 55 22.7	SBb	134	10.41	0.27	3.21	3.18	32.8
IRAS F17190+6219	2633868	17 19 31.79	+62 16 47.3	S?	370	11.23	1.38	3.52	3.39	32.0
MCG +10-25-032	60289	17 26 25.86	+58 35 19.4	Sb	120	10.18	0.61	3.43	2.53	35.7
IRAS 17297+5127	60428	17 30 55.75	+51 25 50.4	S?	210	11.31	0.62	3.53	3.44	35.3
MCG +10-25-070	60578	17 36 57.54	+59 12 00.8	Sbc	140	10.60	0.93	3.09	3.63	37.4
2MASX J21470265-0826288	1003693	21 47 02.67	-08 26 28.8	S?	276	11.06	1.07	3.18	3.91	34.8

Columns: See Table 4.