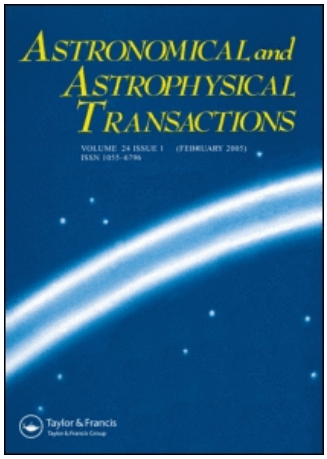


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# What is the source of FIR radiation in spiral galaxies?

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# WHAT IS THE SOURCE OF FIR RADIATION IN SPIRAL GALAXIES?

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We consider the main source of far infrared radiation (FIR) in normal spiral galaxies in the IRAS wavelength range 40–120 $\mu$. There are two competing propositions: (a) the radiation comes from dust heated by young massive stars and (b) there is a second component comparable to or exceeding the first one which is associated with HI-related cool dust heated by a general interstellar radiation field (GISRF) generated by an old stellar disk ("cirrus" component). Here an analysis is given of optical and FIR data and masses of dust and gas for two subsamples of H$\alpha$-detected galaxies separated by their color temperatures of FIR-radiation to compare properties of "cool" and "warm" galaxies. The results give strong evidences in favor of the first proposition claiming that the bulk of FIR is related to star formation even for the subsample of "cool" galaxies. Cirrus radiation should prevail at wavelengths beyond the IRAS range. Differences between "cool" and "warm" galaxies may be accounted for by a different star formation efficiency, which correlates with color temperature of dust.

## 1 INTRODUCTION

In this work we compare two components of far infrared radiation from spiral galaxies which are related to the presence of young massive stars and to cool dust heated by old stars. We consider far infrared radiation (FIR) data obtained by IRAS in the range 40–120 $\mu$m (60 $\mu$m and 100 $\mu$m bands) for normal spiral galaxies which have neither optically found active nuclei nor bursts of star formation which may enhance their long-wavelength radiation.

There is much evidence that FIR radiation from galaxies is directly or indirectly associated with blue stellar light heating interstellar dust. The main questions are: (1) to what extend does the FIR activity reflect the rate of star formation (SFR), and (2) what is the role of the "cool" of cirrus component due to interstellar dust heated up by the aggregate of stars in the old disk.

The available data show that $L_{\rm FIR}$ correlates well with $L_{\rm H\alpha}$ (the accepted present high-mass star formation rate indicator), radio continuum, and blue luminosity, $L_B$.

Some two- or multi-component models have been proposed to explain quantitatively the correlations observed and the measures FIR colors. It is worth noting here the most fundamental ones.

The model proposed by Lonsdale, Persson and Helou (1987, hereafter LPH) assumes that all galaxies have two main components to the FIR which have their own characteristic temperatures. The "cool" or cirrus component is dominated by the general interstellar radiation field (GISRF). It has a temperature of 16–20 K and does not depend strongly on the radiation of young stars if star formation is not too intense all over the galaxy. The "warm" component is powered by star-forming regions and has a characteristic temperature of 50–60 K. In the proposed model of LPH, the cool component in almost all normal spirals is responsible for 50–70% of the total FIR.

de Jong *et al.* (1984) also proposed a two-component model to explain their data: the cool component powered by the GISRF with a temperature of about 25 K and the warm component, whose source is interstellar dust associated with HII regions and molecular clouds heated by O stars. The warm component has a temperature of about 50 K. These authors conclude that a high SFR will be indicated by a high color temperature.

Based on a study of over 3500 galaxies, Bothun, Lonsdale and Rice (1989) conclude that a cool component powered by the GISRF is an important contributor to the total FIR luminosity due to the fact that the overall distribution of the color temperature, derived $F_{60}/F_{100}$ (where $F_{60}$ and $F_{100}$ are IRAS fluxes in Jy at 60 $\mu$m and 100 $\mu$m, respectively), is "skewed away" from values typically associated with high-mass star formation regions. These authors propose that the dominant source of FIR can be determined by the color temperature. They further conclude that because FIR luminosity scales well with disk area and disk mass, it must be closely associated with a spatially extended component (i.e. dust in diffuse HI regions heated by the GISRF). Moreover, for galaxies with low color temperatures, they find a "good relation" between the strength of the GISRF (blue surface brightness) and the FIR emissivity per H atom. According to these authors UV-heated dust is the main FIR contributor only for galaxies with the most "warm" FIR spectra ($F_{60}/F_{100} > 0.5$); for other galaxies the main contributor is dust heated by old disk stars.

Xu and De Zotti (1989), based on their analysis of FIR of Markarian galaxies, find that a three-component model (with hot, warm and cool components) better describes the properties they observe. They confirm that the existence of a cool component explains the color temperatures derived from IRAS fluxes. Xu and De Zotti also propose that the cool component contributes to a significant part of the FIR (IRAS fluxes); they estimate the relative contributions of the warm and cool components to be about equal.

In an analysis of the source of FIR in the Galaxy based on infrared and submillimeter data, Cox, Krügel, and Mezger (1986) predicted that the warm component (powered by star-forming regions) contributes more than the cool component(s) (powered by the GISRF) to the total FIR. They give the warm component a contribution of about 50% and the cool about 40% (the "hot" component contributes the remaining 10%).

Sauvage and Thuan (1992), in an effort to support the argument in favor of the existence of a significant cirrus component in FIR radiation from galaxies, considered the observed decrease of the $L_{\rm FIR}/L_{\rm H\alpha}$ ratio along the Hubble type sequence – from early to late type galaxies. This decrease may be explained by considering that there is a minimum contribution by the GISRF to the observed FIR in galaxies with weak star formation. According to Sauvage and Thuan (1992), the mean cirrus contribution to FIR exceeds 50% for galaxies of all morphological types but the latest (Scd-Sdm). This argument is not very strong, however, because $L_{\rm H\alpha}$, unlike $L_{\rm FIR}$, is most sensitive to the most massive stars which ionize gas, so the decrease in this ratio towards the late-type galaxies may just be caused by a relative deficiency of stars on the upper end of initial mass function (IMF) in galaxies with a weak SFR.

There exist, on the other hand, arguments against the multicomponent models accounting for $F_{60}$–$F_{100}$ fluxes. For example, Devereux and Young, (1990a) express their doubts in a paper which shows that the observed FIR can be accounted for considering only massive stars. This leaves no need for a luminous cool component. Their main argument against the two-component model is that it is unreasonable to assume that almost all galaxies have the same relative amounts of "warm" and "cool" dust. This conclusion comes from the clearly defined mean temperature of all galaxies observed (standard deviation is surprisingly small).

Devereux and Young claim that the $L_{\rm FIR}/L_{\rm H\alpha}$ ratios are close to the expected values for the HII regions, so there is no need to introduce a cirrus component (see, however, critical comments to these arguments by Sauvage and Thuan, 1992).

A detailed analysis of the FIR brightness of close galaxies may be interpreted both by using a cirrus component (M31: Walterbos and Schwering, 1987; M33: Deul, 1989) and by ascribing all radiation to young massive stars heating the dust (NGC 6946: Devereux and Young, 1993).

Among the other arguments it is interesting to note that the $L_{\rm FIR}$ of galaxies weakly correlates with the mass of neutral gas, but is well correlated with the mass of $H_2$ for both warm and cool galaxies (according to their $F_{60}/F_{100}$ ratio) (Young *et al.*, 1989), although one would expect that the cirrus contribution is more essential for the "cool" galaxies. A similar conclusion was drawn for the H$\alpha$ luminosity: $L_{\rm FIR}/L_{\rm H\alpha}$ is correlated for both warm and cool galaxies (Devereux and Young, 1990a). FIR radiation from HI-deficient spiral galaxies in the Virgo Cluster gives evidence against a cirrus component, too: even though most of their interstellar gas is in molecular form, they have above the same color temperatures and $L_{\rm FIR}/M_{\rm H_2}$ ratios as galaxies with normal gas content (Leggett, Brant and Mountain, 1987).

Here, a more detailed analysis of the problem is made and the conclusion is reached that the bulk of FIR radiation in the 60–100 $\mu$m range is related to the formation of massive stars so there is no need to decompose FIR spectra into two comparable components of different nature.

In Section II we analyze the possible factors which may determine the observed $F_{60}/F_{100}$ ratios for galaxies. In Section III we analyze the observational data. In Section IV we summarize our conclusions.

## 2 ON THE SIGNIFICANCE OF THE COOL COMPONENT

In the frame of two-component models the warm component of FIR radiation is related to young stars and the cool (cirrus) component is due to the GISRF:

$$\mathrm{FIR_{total}} = \mathrm{FIR_{warm}} + \mathrm{FIR_{cool}}. \tag{1}$$

Hence, one may expect the contribution of the second component to be more essential for galaxies with lower color temperature, so its significance may be revealed by the comparison of the properties of "warm" galaxies (WG) and "cool" galaxies (CG) chosen by their FIR colors, or flux ratios $F_{60}/F_{100}$.

We consider two limiting cases. Case A: all the FIR radiation comes from the HI-related interstellar dust which is more or less homogeneously distributed in the stellar disk and heated mostly by old stars (the cirrus component). Case B: FIR comes from the regions of star formation. Here we investigate the main factors which determine the temperature of the dust in these cases.

Case A

Let $\tau$ be the optical thickness of the disk for stellar radiation, $L_*$ the optical luminosity, $M_{\mathrm{dust}}$ and $\sigma_d$ are the mass and surface density of the dust layer, $T$ is the temperature of radiation. Then, from the condition of radiative balance we have for FIR luminosity:

$$L_{\mathrm{FIR}} \sim L_*(1-\exp(-\tau)) \sim M_{\mathrm{dust}} \int_0^\infty B_\lambda(T) Q_\lambda \, d\lambda, \tag{2}$$

where $Q_\lambda$ is efficiency of emission and $B_\lambda(T)$ is the Planck function. Usually a law $Q_\lambda \sim \lambda^{-n}$ is adopted and $n = 1$ or 2. Then $L_{\mathrm{FIR}} \sim M_d T^{4+n}$, so from (2) it follows that:

$$T \sim [L_*(1-\exp(-\tau))/M_{\mathrm{dust}}]^{1/4+n}. \tag{3}$$

Substituting $L_*/M_d$ with the local ratio $I_*/\sigma_d$, where $I_*$ is the absorption-free optical surface brightness, $\sigma_d$ is the surface density of the dust, we have

$$T \sim [I_*(1-\exp(-\tau))/\sigma_d]^{1/4+n}. \tag{4}$$

The optical thickness of galactic disks is the matter of controversy, so we consider two limiting cases:

(a) $\tau \ll 1$ (transparent disk). Taking into account that $\sigma_d \sim \tau$, we obtain:

$$T \sim I_*^{1/4+n}, \tag{5}$$

$$L_{\mathrm{FIR}} \sim \tau L_*.$$

(b) $\tau \gg 1$ (opaque disk):

$$T \sim \left[\frac{I_*}{\sigma_d}\right]^{1/(4+n)}, \tag{6}$$

$$L_{\rm FIR} \sim L_*.$$

In the Case (a) $T$ should decrease along the radius of the galaxy parallel to $I_*$, so that in the range of two scale lengths of the disk one can expect the temperature to change by a factor of 1.4–1.5. Note that this does not agree with the observation of FIR brightness in nearby galaxies (M31 and M33) where the temperature is approximately constant along the radius. One may expect that the case of the transparent disk is more suitable for the outer regions of S-galaxies and for S0-galaxies where the density of interstellar matter is definitely low.

In the case (b) of the opaque disk, as one can see from (6), the dust temperature should change along $R$ more slowly than in the first case, because both the brightness of the disk and the density of the ISM falls along $R$. Hence, if the Case A we consider here is valid, then the CG are galaxies which have low disk surface brightness and/or high surface density of dust, independent of the star formation rate in the galaxy.

Case B

We use a simplified model where every region of star formation is surrounded by a dust envelope with the optical thickness for heating stellar radiation $\tau_s$ and radius $R_{\rm en}$. The total mass of the dust in the envelope is proportional to $\tau_s R_{\rm en}^2$, so by analogy with (3) we obtain:

$$T \sim [L_*(1-\exp(-\tau))/\tau_s R_{\rm en}^2]^{1/4+n}. \tag{7}$$

Here $L_*$ is the luminosity of the young stars. For the transparent envelope, $\tau_s \ll 1$ so

$$T \sim [L_*/R_{\rm en}^2]^{1/4+n}, \tag{8}$$

$$L_{\rm FIR} \sim L_* \tau_s.$$

So in this case the temperature of the dust does not depend on the amount of dust in the envelope in a direct way.

For the other limiting case ($\tau_s \gg 1$)

$$T \sim \left(\frac{L_*}{M_{\rm dust}}\right)^{1/4+n} \tag{9}$$

Here, $M_{\rm dust}$ is the mass of the dust in the inner layer of the envelope where absorption of most of the radiation takes place ($\tau_s \sim 1$). This mass has to be larger (hence the temperature is lower) for the more extended envelope which surrounds the source of a given luminosity, $L_*$.

It is interesting to note that if the clumpiness of the envelope leads to a partial absorption-free leakage of the radiation flux, it may reduce $L_{\rm FIR}$ without changing the dust temperature.

So, in Case B "cool" galaxies are the galaxies which have a lower luminosity of young stars per unit mass of dust or they are those which have different geometrical properties of the dusty envelopes which must be more extended.

Consider now the expected differences between WG and CG by the comparison of correlations and ratios between the observable FIR-related parameters for the

two competing cases accounting for CG: either their FIR comes preferentially from cirrus heated by GISRF (Case A) or, like for the WG, it is connected with SF (Case B). For the WG we tentatively admit Case B.

(a) *The correlations of* $L_{\rm FIR}$ *with* $L_{\rm H\alpha}$.

In Case A, these relations have to be well defined for WG and loose for CG, because $L_{\rm H\alpha}$ is good indicator of star formation which is the main source of FIR for WG. In Case B, the correlations should be equally good for both WG and CG.

(b) *The* $L_{\rm FIR}$-$M_{\rm HI}$ *correlation.*

In Case A, this correlation should be better for CG and worse for WG because HI is connected with the ISM and GISRF which are responsible for the bulk of FIR in CG. In Case B, the correlations should be loose, if they exist at all, for both temperature types of galaxies, because FIR is determined mostly by the local properties of the ISM in star forming regions instead of $M_{\rm HI}$.

(c) *The* $M_{\rm dust}$-$L_{\rm H\alpha}$ *correlation* (where $M_{\rm dust}$ is determined from FIR fluxes).

In Case A, there should be a correlation for WG, but there may not be one for CG because FIR and $L_{\rm H\alpha}$ are related to different energy sources in CG. In Case B, one would expect equally good relationships for both WG and CG, because both parameters depend on energy emitted by young (massive) stars all over the disk.

(d) *The* $M_{\rm dust}$-$M_{\rm HI}$ *and* $M_{\rm dust}$-$L_*$ *correlations* (where $M_{\rm dust}$ is determined from FIR fluxes).

For Case A, one can expect more tight correlation for the CG – because in this case both parameters ($M_{\rm HI}$ and $L_*$) are related to the GISRF. For Case B, warm and cool galaxies may be well mixed.

(e) *The* $M_{\rm dust}$-$M_{\rm H_2}$ *correlation.*

In Case A this correlation should be good for WG and loose for CG, because $H_2$ is tightly related to star formation sites in galaxies. In Case B this correlation should be equally good for both groups of galaxies.

(f) *The* $L_{\rm FIR}$-$L_{\rm H\alpha}$ *ratio.*

From (1) it follows that there are two components of this ratio:

$$L_{\rm FIR}/L_{\rm H_\alpha} = (L_{\rm FIR})_{\rm SF}/L_{\rm H_\alpha} + (L_{\rm FIR})_{\rm GISRF}/L_{\rm H_\alpha}. \qquad (10)$$

The first term is related to star formation, the second one is connected with the GISRF.

In Case A, the second term is essential for CG and insignificant for WG, so we may expect this ratio to be higher for CG. For Case B the second term disappears and the situation becomes more vague. If CG are galaxies

which, for some unknown reason, have more extended dust envelopes (gaseous clouds) around regions of SF of given luminosity, then according to (8) and (9), the ratio depends on the transparency of these region (it has to be higher in the opaque medium). On the other hand, a difference in star formation efficiency (SFE) does not change this ratio because both the numerator and the denominator vary similarly with SFR independent of the total mass of the gas. Finally, if the lower temperature is caused by the steepness of the initial mass function (IMF), then this ratio is higher for CG (as in Case A) because $L_{\mathrm{H}\alpha}$ is more sensitive to the number of highest mass stars.

(g) *Relative mass of FIR-active dust*: $M_{\mathrm{dust}}$–$M_{\mathrm{HI}}$, $M_{\mathrm{dust}}$–$M_{\mathrm{H_2}}$ and $M_{\mathrm{dust}}$–$L_*$ ratios.

$M_d$ is the mass of the dust estimated from FIR, so in Case A in CG it is related to the dust distributed all over the disk. Hence, for CG these ratios have to be higher than for WG, where FIR–active dust is mostly connected with the sites of SF. In Case B these is no reason to suspect a systematic difference in these ratios for CG and WG. Note that in this case these ratios have to be much lower for both CG and WG than those found from the $M_{\mathrm{dust}}$ estimate taken as $0.01 M_{\mathrm{gas}}$, which is in accordance with observations (see e.g. Young *et al.*, 1989, Devereux and Young, 1990 b).

## 3 DATA AND DISCUSSION

The data used are presented in Table 1. One hundred galaxies were found which have H$\alpha$ integral fluxes measurements by Kennicutt and Kent (1983), Kennicutt *et al.* (1987) and Bushouse (the latter were taken from Young *et al.* (1989)). Most of them are Sb–Sc spirals detected by IRAS (Point Source Catalog and Extended Source Catalog), and for many of them molecular or atomic gas mass could be obtained from the available data. Distances and $B$-luminosities were calculated from the redshifts and corrected $B$-magnitudes $B_T^0$ given in the Third Reference Catalog of Bright Galaxies (hereafter, RC3). All galaxies with velocities less than 600 km s$^{-1}$ were excluded, a Hubble constant of H=75 km s$^{-1}$Mpc$^{-1}$ was used and a distance of 20 Mpc was adopted for all Virgo galaxies. All galaxies identified as Seyferts, Lenticulars or having burst of star formation were excluded. The only exception is NGC 3690. which has abnormally high FIR luminosity evidently because of the moderate burst of star formation. This object was excluded from statistical comparisons involving $L_{\mathrm{FIR}}$.

The galaxies are divided into two groups based on the temperatures given in column 9. Galaxies with a temperature lower than 35 K ($n = 1$) are listed in the "cool" part of the table; galaxies with a temperature of 35 K or higher are listed in the "warm" part of the table. This boundary was chosen because it is approximate mean temperature of the sample. It corresponds approximately to $F_{60}/F_{100} = 0.4$. Hereafter, the terms "cool galaxies" ("cool group") and "warm galaxies" ("warm group") will refer to galaxies separated by the above criterion.

**Table 1.** General properties of "cool" and "warm" subsamples of galaxies

| NGC | D(Mpc) | $L_{H\alpha}$ log | $L_{FIR}$ log | $L_B$ log | $M_{HI}$ log | $M_{H_2}$ log | $M_{dust}$ log | $T_{dust}$ | $M_{gas}$ log |
|---|---|---|---|---|---|---|---|---|---|
| Cool Group | | | | | | | | | |
| 157 | 23.3 | 41.48 | 43.37 | 44.22 | 43.25 | – | 40.43 | 34.7 | – |
| 628 | 10.6 | 41.24 | 43.31 | 43.87 | 43.38 | – | 40.22 | 30.0 | – |
| 1058 | 9.4 | 40.14 | 42.32 | 43.11 | 42.83 | – | 39.36 | 28.6 | – |
| 1073 | 16.1 | 40.74 | 42.55 | 43.66 | 42.95 | – | 39.92 | 25.5 | – |
| 1087 | 20.1 | 41.23 | 43.52 | 44.01 | 42.79 | – | 40.44 | 29.9 | – |
| 1232 | 20.8 | 41.54 | 43.22 | 44.27 | 43.42 | – | 41.56 | 18.7 | – |
| 1385 | 18.0 | 41.22 | 43.58 | 43.85 | 42.71 | – | 40.14 | 34.6 | – |
| 1832 | 24.5 | 41.24 | 43.50 | 43.93 | 42.88 | – | 40.19 | 32.7 | – |
| 2276 | 36.5 | 41.71 | 44.09 | 44.21 | 43.16 | 43.36 | 40.76 | 32.9 | 43.57 |
| 2535 | 56.3 | 42.08 | 43.75 | 44.24 | 43.49 | – | 40.52 | 31.7 | – |
| 2763 | 24.0 | 40.93 | 43.00 | 43.61 | 42.69 | – | 39.82 | 31.1 | – |
| 3185 | 17.9 | 39.88 | 42.58 | 43.24 | 41.97 | – | 39.36 | 31.0 | – |
| 3368 | 12.8 | 40.73 | 43.11 | 44.08 | 42.74 | – | 39.96 | 30.7 | – |
| 3430 | 23.4 | 41.22 | 43.12 | 43.84 | 43.11 | – | 39.93 | 31.2 | – |
| 3521 | 10.7 | 41.19 | 43.61 | 44.13 | 43.20 | 43.10 | 40.41 | 31.5 | 43.45 |
| 3627 | 10.6 | 41.19 | 43.70 | 44.19 | 42.32 | 42.94 | 40.40 | 32.7 | 43.03 |
| 4027 | 20.8 | 41.24 | 43.56 | 43.85 | 43.16 | – | 40.31 | 32.0 | – |
| 4152 | 20.0 | 40.83 | 43.10 | 43.46 | 42.64 | – | 39.67 | 34.4 | – |
| 4189 | 20.0 | 40.68 | 43.02 | 43.51 | 42.48 | – | 39.41 | 32.4 | – |
| 4237 | 20.0 | 40.18 | 43.01 | 43.52 | 41.91 | – | 39.95 | 29.7 | – |
| 4254 | 20.0 | 41.77 | 43.91 | 44.34 | 43.30 | 43.42 | 40.81 | 30.1 | 43.67 |
| 4298 | 20.0 | 40.66 | 43.27 | 43.77 | 42.38 | 42.76 | 40.52 | 26.6 | 42.91 |
| 4303 | 20.0 | 41.83 | 43.87 | 44.32 | 43.35 | 43.30 | 40.59 | 32.5 | 43.63 |
| 4321 | 20.0 | 41.63 | 43.81 | 44.44 | 43.07 | 43.47 | 40.72 | 30.0 | 43.62 |
| 4501 | 20.0 | 41.18 | 43.75 | 44.47 | 42.89 | 43.29 | 40.84 | 28.1 | 43.44 |
| 4535 | 20.0 | 41.25 | 43.37 | 44.28 | 43.23 | 43.14 | 40.31 | 29.7 | 43.49 |
| 4548 | 20.0 | 40.63 | 42.84 | 44.16 | 42.34 | 42.68 | 40.44 | 23.5 | 42.84 |
| 4561 | 20.2 | 40.40 | 42.56 | 43.27 | 42.68 | – | 39.10 | 34.8 | – |
| 4567 | 20.0 | 40.58 | 43.73 | 43.68 | 42.62 | 42.96 | 40.61 | 30.5 | 43.12 |
| 4569 | 20.0 | 41.06 | 43.49 | 44.49 | 42.24 | 43.12 | 40.34 | 30.9 | 43.17 |
| 4571 | 20.0 | 40.61 | 42.74 | 43.68 | 42.37 | 42.52 | 40.40 | 23.1 | 42.75 |
| 4595 | 20.0 | 40.18 | 42.52 | 43.35 | 42.16 | – | 40.09 | 29.8 | – |
| 4631 | 10.5 | 41.41 | 43.84 | 44.38 | 43.56 | – | 40.53 | 32.9 | – |
| 4632 | 20.0 | 40.98 | 43.11 | 43.71 | 42.94 | – | 39.86 | 32.0 | – |
| 4647 | 20.0 | 40.89 | 43.25 | 43.67 | 42.19 | 42.72 | 40.15 | 30.1 | 42.83 |
| 4651 | 20.0 | 41.14 | 43.25 | 43.96 | 43.06 | – | 40.09 | 30.9 | – |
| 4654 | 20.0 | 41.13 | 43.65 | 44.09 | 43.03 | 42.81 | 40.36 | 32.2 | 42.23 |
| 4666 | 20.0 | 41.40 | 43.95 | 44.12 | 43.11 | – | 40.80 | 30.8 | – |
| 4689 | 20.0 | 40.83 | 43.02 | 43.86 | 42.84 | 42.79 | 40.06 | 28.6 | 43.12 |
| 4713 | 20.0 | 41.16 | 43.14 | 43.62 | 43.04 | 41.73 | 39.73 | 34.0 | 43.06 |
| 4808 | 20.0 | 41.04 | 43.30 | 43.66 | 43.11 | 41.89 | 39.86 | 34.6 | 43.14 |
| 4900 | 13.2 | 40.40 | 42.85 | 43.19 | 42.19 | – | 39.40 | 34.6 | – |
| 5005 | 15.3 | 40.80 | 43.59 | 44.08 | 42.27 | – | 40.50 | 29.9 | – |
| 5033 | 14.3 | 41.03 | 43.47 | 44.02 | 43.30 | – | 40.32 | 30.9 | – |
| 5055 | 9.6 | 41.22 | 43.56 | 44.15 | 43.25 | 43.20 | 40.67 | 28.1 | 43.53 |
| 5194 | 9.4 | 41.50 | 43.88 | 44.27 | 42.95 | 43.47 | 40.62 | 32.2 | 43.84 |
| 5248 | 16.1 | 41.16 | 43.55 | 43.95 | 43.10 | – | 40.22 | 33.1 | – |
| 5350 | 33.6 | 40.83 | 43.40 | 44.05 | 43.20 | – | 40.46 | 28.3 | – |

**Table 1.** Continued

| NGC | D(Mpc) | $L_{H\alpha}$ log | $L_{FIR}$ log | $L_B$ log | $M_{HI}$ log | $M_{H_2}$ log | $M_{dust}$ log | $T_{dust}$ | $M_{gas}$ log |
|---|---|---|---|---|---|---|---|---|---|
| Cool Group | | | | | | | | | |
| 5364 | 17.0 | 41.08 | 42.87 | 43.94 | 42.95 | – | 40.28 | 25.1 | – |
| 5474 | 7.2 | 40.08 | 41.78 | 42.98 | 42.43 | – | 38.95 | 27.4 | – |
| 5480 | 28.1 | 40.98 | 43.37 | 43.69 | 42.47 | – | 40.14 | 31.8 | – |
| 5585 | 7.7 | 40.13 | 41.73 | 43.14 | 42.57 | – | 38.92 | 27.1 | – |
| 5633 | 34.3 | 41.11 | 43.42 | 43.82 | 42.77 | – | 40.25 | 31.0 | – |
| 5676 | 31.5 | 41.46 | 43.94 | 44.27 | 43.17 | – | 40.78 | 30.9 | – |
| 5746 | 23.3 | 41.14 | 42.97 | 44.46 | 42.92 | – | 40.82 | 21.7 | – |
| 5774 | 21.3 | 40.84 | 42.54 | 43.45 | 43.09 | – | 40.10 | 23.8 | – |
| 5775 | 22.8 | 41.19 | 43.83 | 44.02 | 43.25 | – | 40.66 | 31.0 | – |
| 5806 | 18.4 | 40.65 | 42.90 | 43.58 | 42.22 | – | 39.78 | 30.3 | – |
| 5850 | 34.3 | 40.45 | 43.06 | 44.30 | 43.05 | – | 40.57 | 24.2 | – |
| 5962 | 27.5 | 41.26 | 43.71 | 43.98 | 42.83 | – | 40.40 | 32.7 | – |
| 5970 | 27.3 | 41.17 | 43.27 | 43.93 | 42.82 | – | 40.29 | 28.9 | – |
| 6015 | 14.9 | 41.00 | 42.81 | 43.71 | 42.96 | – | 39.78 | 29.4 | – |
| 6070 | 27.0 | 41.14 | 43.44 | 44.02 | 43.04 | – | 40.30 | 30.6 | – |
| 6106 | 20.2 | 40.90 | 42.64 | 43.51 | 42.72 | – | 39.70 | 29.5 | – |
| 6181 | 33.2 | 41.51 | 43.87 | 44.13 | 43.09 | – | 40.45 | 34.2 | – |
| 6207 | 14.0 | 40.79 | 42.84 | 43.46 | 42.47 | 41.51 | 39.57 | 32.3 | 42.52 |
| 6412 | 21.8 | 40.84 | 42.97 | 43.64 | 42.73 | – | 39.98 | 29.0 | – |
| 6643 | 24.0 | 41.40 | 43.71 | 44.09 | 43.00 | 42.74 | 40.60 | 30.3 | 43.19 |
| 6814 | 20.2 | 41.09 | 43.31 | 43.87 | 42.84 | – | 40.23 | 29.9 | – |
| 7217 | 14.8 | 40.75 | 43.03 | 43.92 | 42.16 | 42.33 | 40.11 | 28.2 | 43.22 |
| 7392 | 40.0 | 41.17 | 43.52 | 44.09 | 43.01 | – | 40.47 | 29.6 | – |
| 7716 | 34.2 | 40.79 | 42.85 | 43.86 | 43.01 | – | 39.77 | 29.9 | – |
| 7723 | 24.0 | 40.86 | 43.28 | 43.92 | 42.49 | – | 39.98 | 32.7 | – |
| 7741 | 11.9 | 40.52 | 42.44 | 43.37 | 42.53 | – | 39.45 | 28.9 | – |
| Warm Group | | | | | | | | | |
| 337 | 23.6 | 41.41 | 43.42 | 43.87 | 43.16 | – | 39.98 | 36.0 | – |
| 1022 | 20.1 | 40.54 | 43.69 | 43.59 | – | – | 39.78 | 40.0 | – |
| 1084 | 18.0 | 41.41 | 43.78 | 43.94 | 43.01 | – | 40.30 | 35.2 | – |
| 2139 | 22.6 | 41.25 | 43.39 | 43.76 | 43.15 | – | 39.90 | 35.3 | – |
| 2146 | 16.0 | 41.99 | 44.34 | 43.97 | 42.95 | 43.17 | 40.36 | 44.8 | 43.37 |
| 2339 | 30.6 | 41.56 | 44.07 | 44.17 | 43.13 | 43.25 | 40.36 | 38.8 | 43.50 |
| 2445 | 55.8 | 41.87 | 43.86 | 43.85 | 43.31 | – | 40.24 | 37.3 | – |
| 2633 | 32.8 | 41.01 | 44.06 | 43.92 | 43.00 | 42.89 | 40.33 | 39.0 | 43.25 |
| 2798 | 25.9 | 41.01 | 43.96 | 43.63 | 42.50 | 41.73 | 39.95 | 44.6 | 42.57 |
| 2964 | 19.7 | 41.17 | 43.51 | 43.75 | 42.60 | – | 39.98 | 35.8 | – |
| 3310 | 16.5 | 41.61 | 43.73 | 43.85 | 43.03 | 41.94 | 39.70 | 45.1 | 43.06 |
| 3351 | 11.1 | 40.84 | 43.19 | 43.78 | 42.54 | – | 39.66 | 35.8 | – |
| 3395 | 23.9 | 41.43 | 43.52 | 43.71 | 42.96 | – | 40.01 | 35.6 | – |
| 3504 | 22.4 | 41.32 | 43.80 | 43.89 | 42.07 | 42.61 | 40.11 | 38.6 | 42.72 |
| 3690 | 44.0 | 42.07 | – | 44.34 | – | 43.34 | 40.84 | 49.8 | – |
| 3994 | 69.4 | 41.96 | 44.11 | 43.80 | – | – | – | 35.2 | – |
| 4038 | 20.3 | 41.89 | 44.04 | 44.16 | 42.85 | 43.09 | 40.48 | 36.5 | 43.29 |
| 4212 | 20.0 | 40.98 | 43.32 | 43.47 | – | 42.65 | 39.48 | 35.3 | – |
| 4299 | 20.0 | 40.97 | 42.85 | 43.24 | 42.50 | – | 39.27 | 36.6 | – |
| 4490 | 10.5 | 41.63 | 43.49 | 43.92 | 43.23 | 41.85 | 39.92 | 36.4 | 43.25 |

**Table 1.** Continued

| NGC | D(Mpc) | $L_{H\alpha}$ log | $L_{FIR}$ log | $L_B$ log | $M_{HI}$ log | $M_{H_2}$ log | $M_{dust}$ log | $T_{dust}$ | $M_{gas}$ log |
|---|---|---|---|---|---|---|---|---|---|
| Warm Group | | | | | | | | | |
| 4294 | 20.0 | 40.97 | 42.90 | 43.59 | 42.73 | 41.67 | 39.40 | 35.4 | 42.77 |
| 6052 | 64.5 | 42.00 | 44.26 | 44.05 | 43.21 | – | 40.36 | 42.3 | – |
| 6217 | 22.4 | 41.19 | 43.57 | 43.83 | 43.21 | – | 40.03 | 35.9 | – |
| 6574 | 31.7 | 41.28 | 44.00 | 44.08 | 42.43 | 43.08 | 40.42 | 36.7 | 43.17 |
| 7479 | 32.6 | 41.25 | 43.96 | 44.33 | 43.26 | 42.86 | 40.45 | 35.6 | 43.41 |
| 7742 | 22.8 | 40.82 | 43.06 | 43.06 | 42.41 | – | 39.57 | 35.2 | – |

Table 1 is arranged as follows: Column (1): NGC number. Column (2): distance $D$ in Mpc calculated using radial velocities given in RC3 ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$), corrected for solar motion and Virgo inflow except in the case of Virgo galaxies where a distance of 20 Mpc was adopted uniformly. Column (3): the logarithm of the H$\alpha$ luminosity in erg s$^{-1}$ calculated using fluxes from Kennicutt and Kent (1983), Kennikutt *et al.* (1987) and Bushouse (see Young *et al.*, 1989). Column (4): the logarithm of the far-infrared luminosity in erg s$^{-1}$ calculated where the fluxes were taken from either the Point Source Catalog or the Extended Source Catalog:

$$L_{FIR} = 1.26 \times 10^{-7} \times 4 \times \pi D^2 (2.58 \times F_{60} + F_{100})$$

where $D$ is the distance in m, and $F_{60}$ and $F_{100}$ are the IRAS fluxes in Jy. Column (5): the logarithm of the blue luminosity in erg s$^{-1}$ calculated from $B_T^0$ given in the RC3. If $B_T^0$ was not available, then $m_B$ was used in conjunction with extinction information. Column (6): the logarithm of the mass of the atomic hydrogen in grams calculated from fluxes given in Bottinelli *et al.* (1984) using the following equation

$$M_{HI} = 4979 \times F_{HI} \times D^2$$

where $D$ is distance in Mpc and $F_{HI}$ is the flux given in the catalog in Jy km s$^{-1}$. Column (7): the logarithm of the mass of molecular hydrogen in grams taken from Young *et al.* (1989) (conversion factor = $2.8 \times 10^{-20}$ cm$^{-2}$/K×km/s). Column (8): the logarithm of the mass of the "FIR" dust in grams calculated using $\lambda^{-1}$ emissivity law (see Young *et al.*, 1989):

$$M_{dust} = 9.74 \times 10^{33} \times F_{100}^2 \times D^2 \times [\exp(144/T_{dust}) - 1].$$

Column (9): color temperature of the FIR in K calculated using $F_{100}/F_{60}$ and assuming a $\lambda^{-1}$ emissivity law (the same temperature is used to calculate the mass of the warm dust, given in column (8). Column (10): the logarithm of the total gas mass in grams calculated by adding the molecular and atomic hydrogen masses.

So we have rather representative samples of galaxies for both temperature groups. Although they are, by no means, not free from observational selection, they

**Table 2.** Correlation coefficients and mean log of ratios (± r.m.s) for different parameters for cool and warm groups of galaxies

| *Relationships* | *Cool galaxies* | | | *Warm galaxies* | | |
|---|---|---|---|---|---|---|
| | k | $\Delta Log$ | n | k | $\Delta Log$ | n |
| log $L_{FIR}$ vs log $L_{H\alpha}$ | 0.67 ± 0.07 | 2.8 ± 0.3 | 60 | 0.78 ± 0.06 | 2.6 ± 0.3 | 39 |
| log $L_{FIR}$ vs log $M_{H_2}$ | 0.77 ± 0.09 | 0.5 ± 0.3 | 19 | 0.75 ± 0.12 | 1.2 ± 0.4 | 16 |
| log $L_{FIR}$ vs log $M_{dust}$ | 0.85 ± 0.03 | 3.3 ± 0.3 | 60 | 0.88 ± 0.04 | 3.8 ± 0.2 | 38 |
| log $L_{FIR}$ vs log $M_{HI}$ | 0.41 ± 0.10 | 0.4 ± 0.5 | 60 | 0.49 ± 0.13 | 0.7 ± 0.4 | 36 |
| log $L_{FIR}$ vs log $L_B$ | 0.73 ± 0.05 | 0.7 ± 0.3 | 61 | 0.82 ± 0.05 | 0.3 ± 0.3 | 38 |
| log $L_{H\alpha}$ vs log $M_{dust}$ | 0.71 ± 0.06 | 1.1 ± 0.3 | 60 | 0.76 ± 0.07 | 1.4 ± 0.3 | 39 |
| log $L_{H\alpha}$ vs log $M_{H_2}$ | 0.66 ± 0.14 | −1.8 ± 0.3 | 19 | 0.59 ± 0.17 | −1.2 ± 0.5 | 17 |
| log $L_{H\alpha}$ vs log $L_B$ | 0.67 ± 0.07 | −2.9 ± 0.3 | 61 | 0.78 ± 0.06 | −2.6 ± 0.3 | 39 |
| log $L_{H\alpha}$ vs log $M_{dust}$ | 0.71 ± 0.06 | 1.1 ± 0.3 | 60 | 0.76 ± 0.07 | 1.4 ± 0.3 | 39 |
| log $M_{dust}$ vs log($M_{HI+H_2}$) | 0.70 ± 0.13 | −3.1 ± 0.3 | 19 | 0.72 ± 0.14 | −3.3 ± 0.3 | 15 |
| log $M_{dust}$ vs log $L_B$ | 0.82 ± 0.04 | −4.0 ± 0.2 | 60 | 0.93 ± 0.01 | −4.1 ± 0.2 | 39 |

nevertheless have approximately the same ranges of distances and FIR, optical and CO-luminosities which allows them to be compared with one another.

Diagrams showing interdependencies between different parameters which may be essential for comparison of two possibilities are shown in Figures 1–7. Table 2 gives coefficients of correlation and mean ratios (in log scale).

Comparison of the expected differences between WG and CG for Cases A and B, discussed in part II, give unambiguous arguments in favor of Case B. FIR luminosities of both temperature groups of galaxies correlate with $L_{H\alpha}$ in a similar manner (Figure 1, see also Young *et al.*, 1989). The relationship between $L_{FIR}$ and $L_{H\alpha}$ for both temperature groups also holds for normalized luminosities $L_{FIR}/L_B$ and $L_{H\alpha}/L_B$ (see Figure 2), although as one can expect $L_{FIR}/L_B$ is to be higher in the mean for warm galaxies in Case A.

There is poor correlation of $L_{FIR}$ with $M_{HI}$ for both temperature groups (Figure 3), in spite of the expectations that the cirrus component of CG have to be associated with dust which is well mixed with HI.

There are no noticeable differences between WG and CG which are expected in the Case A (a, b, c, d). Moreover, the correlation between mass of FIR-emitted dust log $M_{dust}$ and stellar luminosity log $L_B$ is better for the WG (Figure 4) instead of the CG expected in Case A (see Part II). The mass of FIR-detected dust equally correlated with $M_{HI}$ or $M_{H_2}$ for both CG and WG (Figures 5 and 6). This means that the origin of FIR is more related to the presence of young stars then to GISRF not only for WG but also for CG. In other words, the contribution of a cirrus component to the total FIR seems to be small even for galaxies which have low $F_{60}/F_{100}$ flux ratios.

The below-average color temperatures appear to be caused by low SFE (see Part II); that is, by the number of young stars per unit of mass of ISM. An additional argument in favor of the last conclusion is that the CG have lower H$\alpha$ and FIR luminosities in comparison to the mass of the interstellar components $M_{dust}$, or

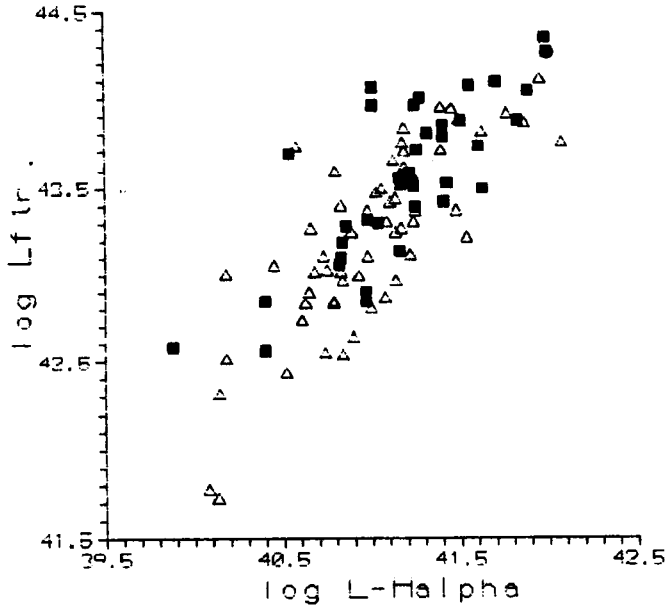


**Figure 1** $L_{\rm FIR}$ vs. $L_{\rm H\alpha}$ for all galaxies in our late-type sample. Cool galaxies are indicated by open triangles and warm galaxies are indicated by closed squares.

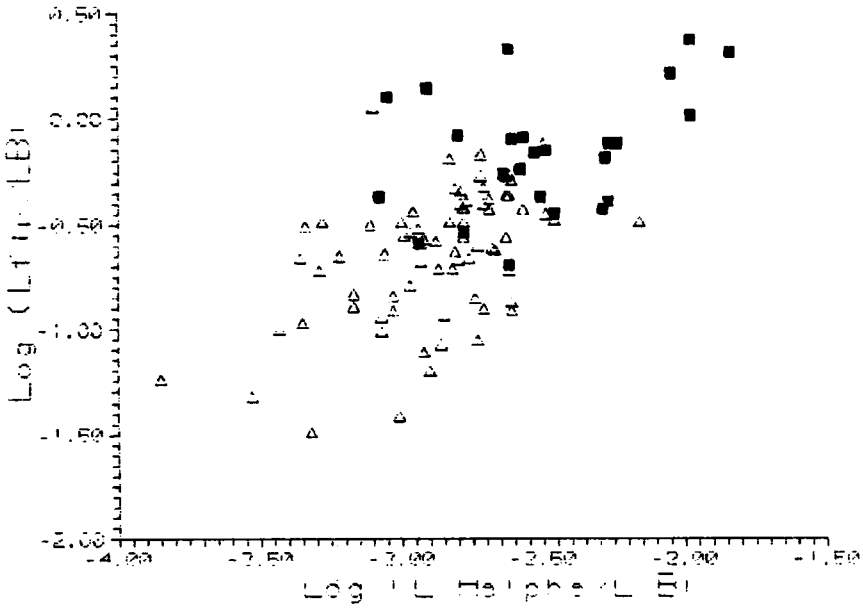


**Figure 2** $L_{\rm FIR}/L_B$ vs. $L_{\rm H\alpha}/L_B$. Cool and warm galaxies are indicated as before.

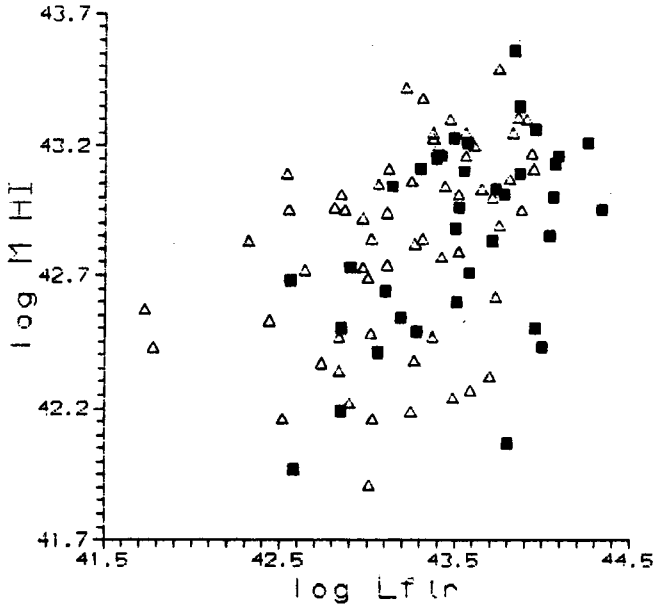


**Figure 3** $L_{\rm FIR}$ vs. $M_{\rm HI}$ for all galaxies in our late-type sample. Cool and warm galaxies are indicated as before.

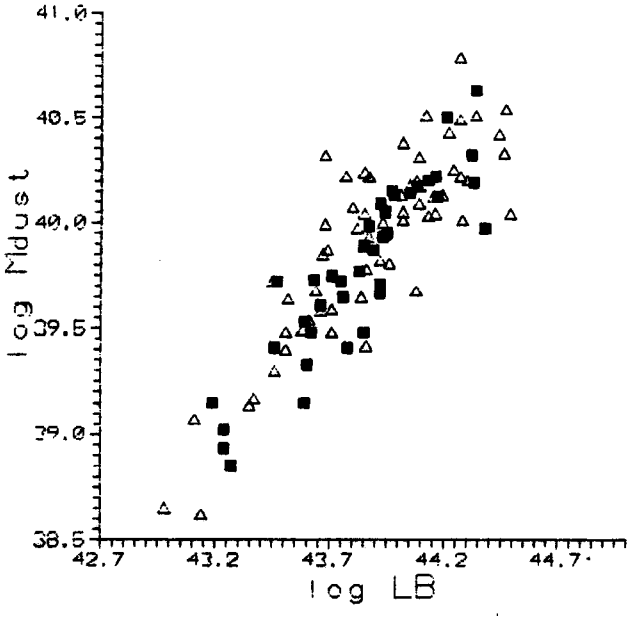


**Figure 4** $M_{\rm dust}$ vs. $L_*$ for all galaxies in our late-type sample. Cool and warm galaxies are indicated as before.

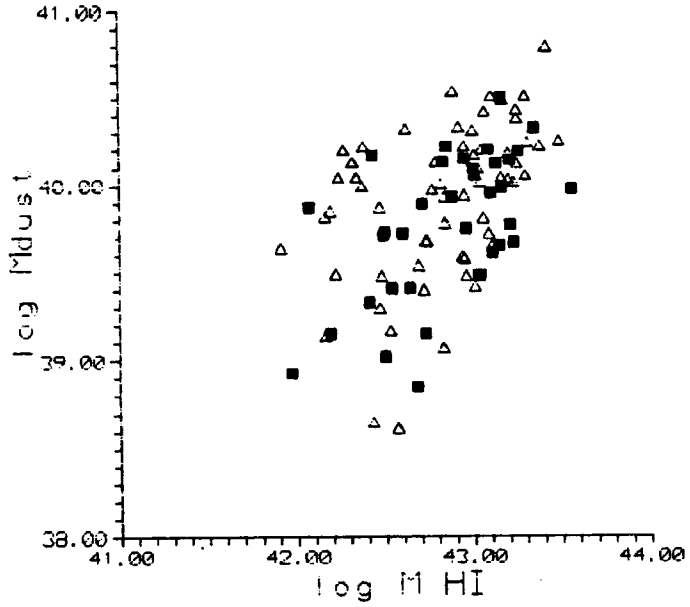


**Figure 5** $M_{\rm dust}$ vs. $M_{\rm HI}$ for all galaxies in our late-type sample. Cool and warm galaxies are indicated as before.

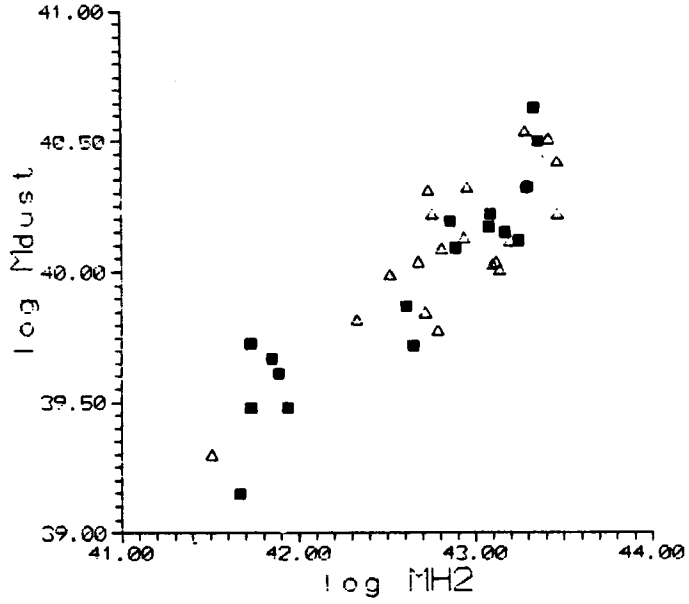


**Figure 6** $M_{\rm dust}$ vs. $M_{\rm H_2}$ for all galaxies in our late-type sample. Cool and warm galaxies are indicated as before.

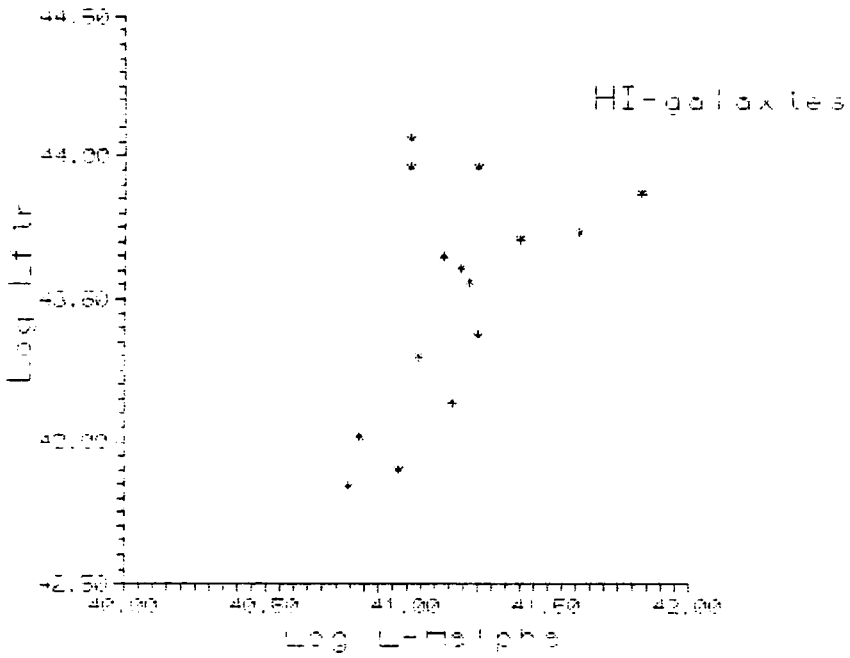


**Figure 7** The same as Figure 1, but for HI-rich galaxies (both temperature subsamples are taken altogether).

$M_{H_2}$ associated with SF (see Table 2). Note, however, that the values of these ratios by themselves can not be considered as arguments in favor of Case B because qualitatively, they are not in conflict with Case A, either. The alternative possibility is that CG and WG differ by IMF of massive stars, but in this case it would reveal itself by different ratio $L_{H\alpha}$ over $L_{FIR}$. The observational data do not confirm it (see Figure 1).

Young *et al.* (1989) have proposed that both molecular clouds and HI may not differ much by their dust temperatures in spite of the different nature of heating. In this case the main source of FIR in the HI-rich galaxies may be GISRF, although in $H_2$-rich systems FIR is associated with young stars. If so, the correlation $L_{FIR}$–$L_{H\alpha}$ have to be poor for HI-rich galaxies. To check it, we compare these luminosities for galaxies which have $M_{H_2} < M_{HI}$ irrespectively on their temperatures (Figure 7). It is evident, that the relationship does not differ significantly from the diagram taken for all galaxies (Figure 1). So it seems that HI-related dust does not play essential role in the FIR of normal spirals.

Direct comparison of $T_{dust}$ and SFE, where SFE is the ratio of $L_{H\alpha}$ to $M_{HI}+M_{H_2}$ is given in Figure 8. It reveals steep dependence of $T$ on SFE: the increasing of $T_{dust}$ at about 20 K corresponds to the enhancing os SFE at approximately ten times.

Assuming the above conclusion (that FIR is related to star formation even in the case of low $T_{dust}$), it is interesting to know which is the best indicator of star

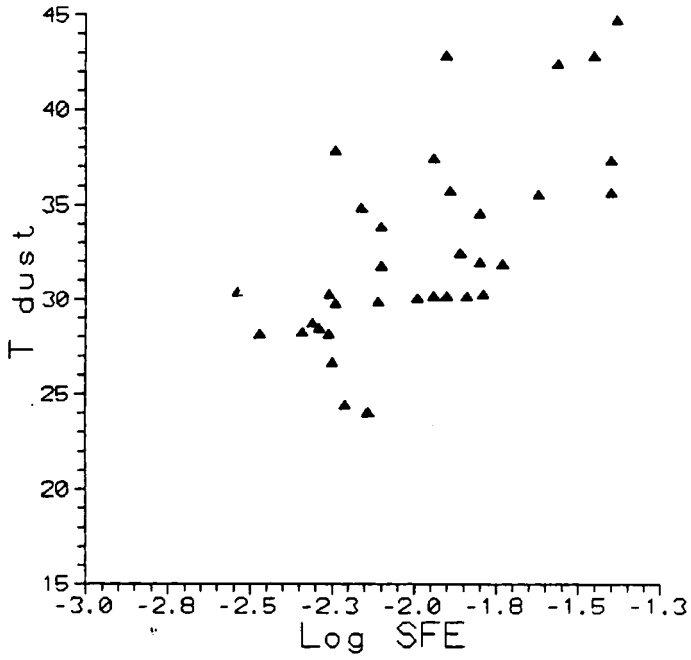


**Figure 8** $T_{\rm dust}$ vs. Star Formation Efficiency SFE = $L_{\rm H\alpha}/(M_{\rm HI+H_2})$.

formation: $F_{60}$, $F_{100}$ or FIR luminosities of the galaxies. In order to do this, we tested our galaxy sample (including both "warm" and "cool" galaxies) for correlations between star formation related parameters and these far infrared luminosities. The quantities used as star formation indicators were $L_{\rm H\alpha}$, the accepted star formation indicator, and $L_{\rm radio}$, an alternative star formation indicator associated with supernova and therefore indicative of, primarily, massive star formation. We also correlate them with $M_{\rm H_2}$, since $H_2$ is related to SF and SF regions. The results of these comparisons are shown in Table 3.

From Table 3, we see that $L_{100}$–$L_{\rm H\alpha}$ is the best correlated among $L_{60}$–$L_{\rm H\alpha}$ and $L_{\rm FIR}$–$L_{\rm H\alpha}$. Also $L_{100}$ correlated best with $M_{\rm H_2}$ in comparison to $L_{60}$ and $L_{\rm FIR}$, although it is not evident that these coefficients are indeed different since the errors allow the coefficient range to overlap (the mean error of correlation coefficients is 0.1). The correlation coefficient that is most clearly the highest in comparison to the others is that of $L_{\rm FIR}$ with $L_{\rm radio}$.

The lower correlation coefficients for relationships with $M_{\rm H_2}$ is most likely due to the fact that $M_{\rm H_2}$ is not an indicator of star formation. It is worth noting that $L_{100}$ has a reliably good correlation for all three SF-related parameters which strengthens the conclusion above that a GISRF-heated dust is not the main source of the radiation even at 100 $\mu$m. So our results clearly show that all three infrared luminosities are good indicators of star formation.

Table 3 Correlation coefficients for FIR and radio parameters of galaxies.

| | log $L_{60}$ | | log $L_{100}$ | | log $L_{FIR}$ | | log $L_{Radio}$ | |
|---|---|---|---|---|---|---|---|---|
| | $k$ | $n$ | $k$ | $n$ | $k$ | $n$ | $k$ | $n$ |
| log $L_{H\alpha}$ | 0.75 | 94 | 0.80 | 94 | 0.79 | 99 | 0.87 | 42 |
| log $L_{Radio}$ | 0.87 | 35 | 0.89 | 35 | 0.93 | 42 | – | – |
| log $M_{H_2}$ | 0.53 | 32 | 0.65 | 32 | 0.54 | 33 | 0.40 | 20 |

For early type (S0/a-E) gas-poor galaxies the situation is more ambiguous. Although for many of these galaxies the FIR-radiation is too weak to be detected, those which have some interstellar gas are often FIR-emitters. The FIR flux ratios of these galaxies (color temperatures) are similar to spiral galaxies (Bally and Thronson, 1989; Wiklind and Henkel, 1989). The correlation between $L_{FIR}$ and $M_{HI}$ for early type galaxies is very weak (Eskridge and Pogge, 1991) which is not the nature of radiation of the cirrus component. However FIR in early type galaxies is found to be related to $M_{H_2}$ in the same manner as for late type galaxies. This indicates that in both early and late type galaxies the same mechanism is probably responsible for the FIR radiation observed (Wiklind and Henkel, 1989). A similar conclusion follows from the ratio of FIR to non-thermal radio luminosities which is approximately the same in the mean as for spiral galaxies (although some S0 galaxies have strong radio excesses probably related to active nuclei) (Bally and Thronson, 1989). So the FIR in early type galaxies probably has its origin in $H_2$-related sites of star formation too. The global SFR of some of these galaxies is low so one can expect that those galaxies with extreme low $L_{FIR}$ may have enhanced FIR because of a cirrus dominated component (see, e.g., Bally and Thornson, 1989). The observed $L_{FIR}$–$M_{H_2}$ relationship agrees with the proposition: there is some excess in the FIR to $M_{H_2}$ ratio for the weakest FIR-emitters, although statistics are too poor yet (see Figure 9, data taken from Wiklin and Henkel, 1989, see also Figure 7 in their article). If this excess is due to cirrus radiation, the total luminosity of this component is less than $10^{43}$ erg s$^{-1}$ (more FIR-luminous galaxies obey relationships similar to the late-type ones) which is less than 10% of the optical luminosity. This reflects the low optical thickness $\tau < 0.1$ of early type galaxies.

To detect a real cirrus component of radiation unrelated to the SF, the spectral data are needed beyond IRAS wavelength bends. The total luminosity of this component may exceed $L_{FIR}$ because it involves most of the interstellar dust in the galaxy. We will refer to this component as the coldest one. Its presence is evident from the observations at longer wavelengths up to 1300 $\mu$m, showing some excess of radiation in the long wavelength tails of spectra (see Chini *et al.*, 1986; Chini and Krügel, 1993; Eales *et al.*, 1989; Stark *et al.*, 1989). Decomposition of the general spectra is very unreliable and ambiguous because there are only a few points in the spectral curve to determine its shape. It is evident however that the input of this coldest component at wavelength in the FIR range up to the 100 $\mu$m must be small:

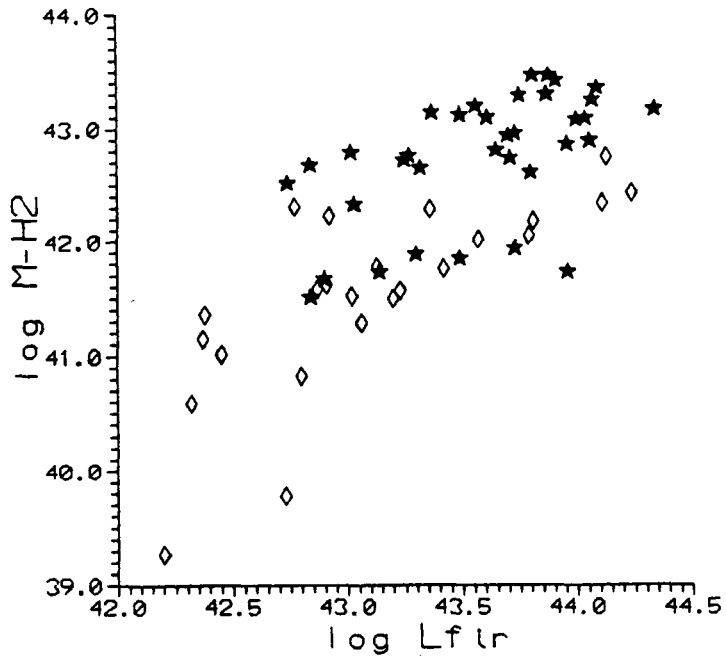


**Figure 9** $L_{\rm FIR}$ vs. $M_{\rm H_2}$ for the spiral galaxies of our sample (asteriks) as well as for the early-type galaxies, taken from Wiklind and Henkel (1989) (diamonds).

otherwise luminosities of galaxies at 100 $\mu$m would show a poor correlation with the star formation rate.

## 4 CONCLUSIONS

In this work spiral galaxies are examined to determine their properties in relation to their FIR color temperatures. It is found that FIR and optical data taken separately for the two temperature groups of galaxies can be explained best by models where FIR luminosity reflects star formation rate for both "cool" and "warm" subsamples. The existence of "cool" radiation associated with the sites of star formation is not in conflict with observations of molecular clouds (GMC) of our Galaxy: some of the sites of star formation have color temperatures similar to the expected ones for the cirrus component (Thronson and Bally, 1987). So a low color temperature may be accounted for by a large fraction of cold GMC without active star formation throughout the galaxy. In this case the mean dust temperature reflects the number of massive stars per unit of mass of gas, or efficiency of star formation, not the input of cirrus component as it is often assumed. SFE changes at about one order of magnitude along the observed range of $T_{\rm dust}$ (25–45 K).

A real cirrus component, not associated with star formation, may reveal itself at longer wavelengths. Luminosities of galaxies taken at 60 $\mu$m and 100 $\mu$m (and their combination $L_{\rm FIR}$) may nearly equally be used as indicators of the star formation rate in spiral galaxies.

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