

MODELS FOR INFRARED EMISSION FROM IRAS GALAXIES

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ABSTRACT. Models for the infrared emission from IRAS galaxies by Rowan-Robinson and Crawford, by de Jong and Brink, and by Helou, are reviewed. Rowan-Robinson and Crawford model the 12-100 μ radiation from IRAS galaxies in terms of 3 components: a normal disc component, due to interstellar 'cirrus'; a starburst component, modelled as hot stars in an optically thick dust cloud; and a Seyfert component, modelled as a power-law continuum immersed in an $n(r) \propto r^{-1}$ dust cloud associated with the narrow-line region of the Seyfert nucleus. The correlations between the luminosities in the different components, the blue luminosity and the X-ray luminosity of the galaxies are consistent with the model. Spectra from 0.1 to 1000 μ m are predicted and compared with available observations.

de Jong and Brink, and Helou, model IRAS non-Seyfert galaxies in terms of a cool (cirrus) component and a warm (starburst) component. de Jong and Brink estimate the face-on internal extinction in the galaxies and find that it is higher in galaxies with more luminous starbursts. In Helou's model the spectrum of the warm component varies strongly with the luminosity in that component. The 3 models are briefly compared.

1. INTRODUCTION

In this paper I review 3 attempts to interpret the far infrared spectra of IRAS galaxies, by Crawford and Rowan-Robinson (1986), by de Jong and Brink (1986) and by Helou (1986).

The main properties we have to explain are:

- (i) the great range of far infrared luminosities in IRAS galaxies, from 4×10^7 – 4×10^{12} L_{\odot} at 60 μ (Fig 1).
- (ii) the great range of ratio of far infrared to optical luminosity, in IRAS galaxies, from 0.05 to several hundred (Soifer et al 1984, Rowan-Robinson et al 1986),
- (iii) the correlation of $L_{\text{FIR}}/L_{\text{opt}}$ with $S(100\mu)/S(60\mu)$ (de Jong et al 1984, Rowan-Robinson et al 1986),
- (iv) the distribution of IRAS galaxies in the IRAS colour-colour diagrams,
- (v) the fact that many Seyferts show a peak at 25 μ (Miley et al 1984, de Grijs et al 1985).

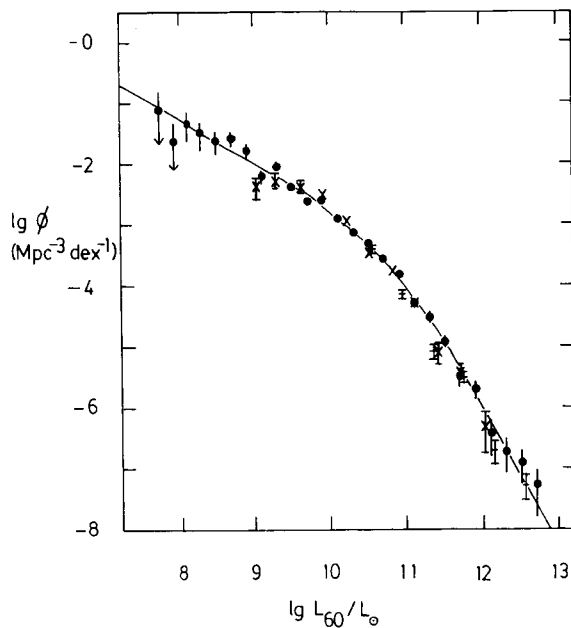


Fig 1 60 μ m luminosity function for IRAS galaxies: filled circles (Lawrence et al 1986), crosses (Soifer et al 1986), x's (Rieke and Lebofsky 1986, assuming their $L_{\text{IR}} = 2.7 L_{60}$), calculated for $\Omega = 1$, $H_0 = 50$. The solid curve is the two power-law fit of Lawrence et al.

Far infrared (10–1000 μ) radiation can be expected from a normal spiral galaxy due to a variety of mechanisms. Dust in interstellar neutral hydrogen clouds, illuminated by the general interstellar radiation field, radiates prominently at 100 μ and in our Galaxy has been called the infrared 'cirrus' (Low et al 1984). The cirrus is also seen at 60 μ and more recently has been found to be radiating surprisingly strongly at 25 and 12 μ (Gautier and Beichman 1985, Boulanger et al 1985). To radiate significantly at 12 μ , interstellar grains must include a grain population much hotter than the thermal equilibrium temperature and it has been postulated that this population consists of very small grains (radius 0.001–0.003 μ , ~ 50 atoms) or, alternatively, of large molecules (Sellgren 1984, Leger and Puget 1984). Dust in the surface layers of molecular clouds will also be heated by the interstellar radiation field and in addition may be heated by young OB associations recently formed from the cloud complex. However uv photons will not be able to penetrate further than $A_V \sim 1$ into the clouds, so the bulk of the dust within molecular clouds should be at a temperature significantly lower than that in the HI clouds. Dust in the vicinity of protostars and newly formed stars embedded in molecular clouds will also radiate strongly in the far infrared. Crawford and Rowan-Robinson (1986) have shown that compact, high surface-brightness IRAS sources in the Galactic plane, many of which are associated with compact HII regions, can be modelled as hot stars embedded in a high optical depth dust cloud.

Finally high optical-depth circumstellar dust shells around late type stars, OH-IR sources and young planetary nebulae, form a related population of far infrared emitters which dominate the 12 and 25 μ emission from the bulge of our Galaxy (Habing et al 1985, Rowan-Robinson and Chester 1986) and could make a significant contribution to the 10–25 μ emission from the discs of some quiescent spirals like M31.

Turning to active galaxies, some categories like 'starburst' galaxies (Balzano 1983) may differ from normal spirals in the far infrared only in the relative proportions of the different ingredients discussed above. On the other hand galaxies with a quasar-like nucleus, eg Seyfert 1 galaxies, might be expected to produce additional far infrared radiation. Both quasars and Seyferts are known to have power-law spectra in the wavelength range 1-10 μ , with spectral index α ($S(\nu) \propto \nu^{-\alpha}$) in the range 0.5 -2 (Neugebauer et al 1979, Ward et al 1986). At visible and ultraviolet wavelengths quasars also have roughly power-law continua with a mean spectral index around 0.5 (Richstone and Schmidt 1980, Cheney and Rowan-Robinson 1981). Where such a nuclear source is located in a galaxy containing dust, for example a spiral galaxy, some of this visible and ultraviolet light will be absorbed by dust and reemitted in the far infrared.

The papers by de Jong and Brink and by Helou specifically exclude Seyferts from consideration. All three papers attempt to account for starburst and 'cirrus' components.

2. THE ROWAN-ROBINSON AND CRAWFORD STUDY

2.1 The Sample Studied

We have selected from the IRAS Point Source Catalog all those sources which have high-quality fluxes in all 4 IRAS bands (12, 25, 60, 100 μ), which are not flagged as associated with months-confirmed small extended sources (SES) in any band, and which are associated with catalogued galaxies. Associations were only accepted if they were within 2' of the IRAS position. Where accurate optical positions are available for the galaxy the positional agreement with the IRAS source is generally better than 10" for this sample. After deletion of 2 sources whose far infrared spectra were clearly those of stars (and for which there were also stellar associations) and of the planetary nebula NGC 6543, which picked up a spurious association with a nearby galaxy, the sample consisted of 208 galaxies.

The SES-flag condition was necessary both to eliminate contamination by cirrus emission and to ensure that the fluxes measured by IRAS represent the total flux from the galaxy. Where the emission from a galaxy is extended with respect to the IRAS beam the fluxes reported in the Point Source Catalog may be seriously underestimated and corresponding IRAS colours will be distorted.

167 have measured velocities. For the 41 which do not, we clearly have no information on their activity type either (see below). 24 are elliptical or lenticular, 127 are spiral or irregular, 57 are of unknown Hubble type, 18 are starburst or HII galaxies, 15 are Seyfert 1, 23 are Seyfert 2. Arp, Vorontsov-Velyaminov and Zwicky compact galaxies appear to be represented on a basis proportional to their frequency in the general galaxy population.

2.2 IRAS Colour-Colour Diagrams

Figures 2 a,b show the 12-25-60 and 25-60-100 μ colour-colour diagrams for the sample, with different symbols for starburst (+HII), Seyfert and other galaxies. Some striking features of this distribution are immediately apparent. (a) The starburst galaxies occupy well-defined areas of the 2 diagrams and in fact have colours very similar to those of compact HII regions in our Galaxy (Crawford and Rowan-Robinson 1986); (b) the bulk of the 'normal' galaxies (non-Seyfert, non-starburst) lie in a band stretching from the zone occupied by the starburst galaxies towards warmer S(25)/S(12) colours in Fig 2a and towards cooler S(100)/S(60) colours in Fig 2b; (c) the Seyferts spread out from this band towards lower values of S(60)/S(25), indicating the presence of a component peaking at 25 μ . Such a component was first noticed by Miley et al (1984) in 3C390.3. Low values of S(60)/S(25) have been successfully used as a criterion for selecting Seyfert galaxies by de Grijp et al (1985).

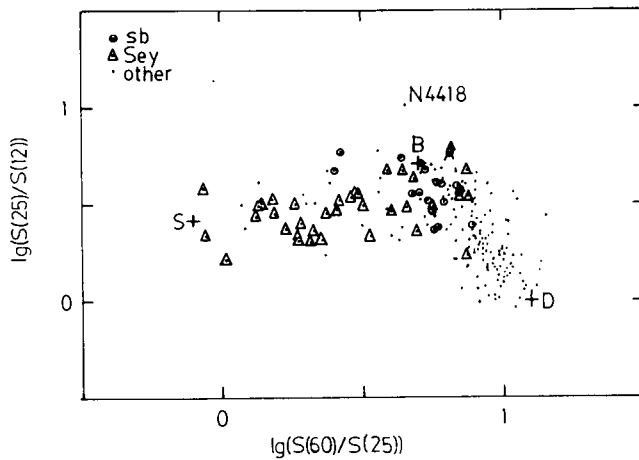
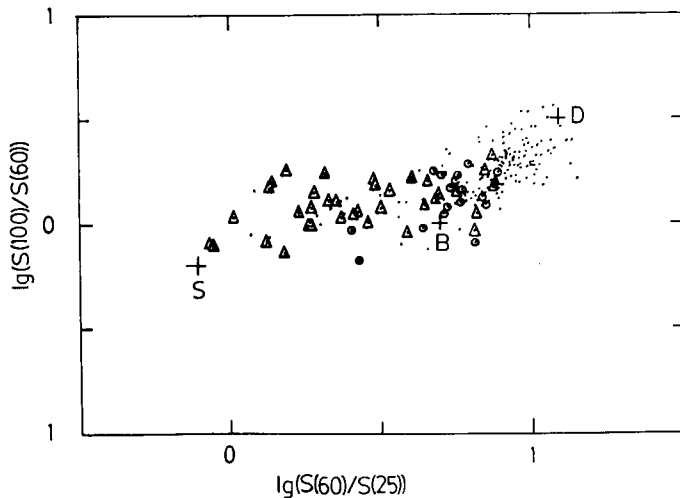


Fig 2 IRAS colour-colour diagrams for unresolved IRAS galaxies with high-quality fluxes in all 4 bands. Circled dots are star-burst (or HII) galaxies, triangles are Seyferts, dots are neither of these or unclassified to date. The crosses labelled D, B, S, are the adopted colours of the 'disc', 'starburst' and 'Seyfert' components used to synthesize the observed far infrared spectra.



2.3 A 3-Component Model for Far Infrared Spectra of Galaxies

As a first step towards understanding the range of galaxy far infrared spectra implied by Fig 2, we postulate that these spectra can be considered as a mixture of 3 components: (1) a normal 'disc' component, (2) a 'starburst' component, (3) a 'Seyfert' component. The colours adopted for these 3 components are indicated in Fig 2 by the letters D, B and S, and Fig 3 shows the corresponding spectra of the 3 components normalised to $12\ \mu$, after colour-correction for the effect of the IRAS pass-bands. We now discuss models for each of these 3 components.

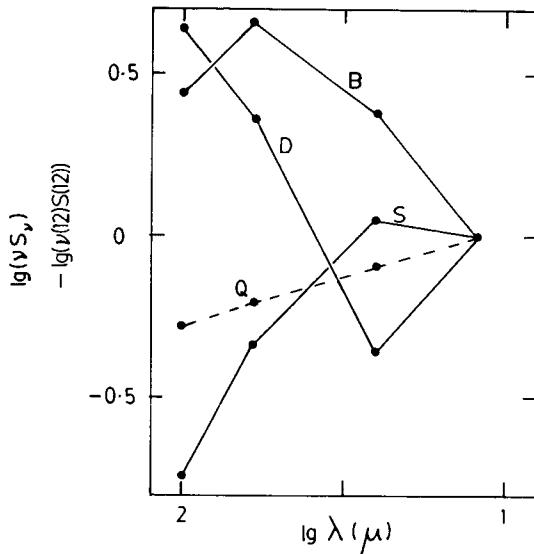


Fig 3 12-100 μ spectra, normalized to $12\ \mu$, of adopted model components: D('disc'), B('starburst') and S('Seyfert'). The broken curve Q is the $\alpha = 0.7$ power-law ('quasar') component considered for 3C273 (Fig 8c).

In Fig 4a the spectrum of the 'disc' component is compared with the spectrum of an isolated piece of cirrus in our Galaxy, a small cloud of interstellar neutral gas and dust with $A_V \sim 0.15$ presumably illuminated by the interstellar radiation field (Boulanger et al 1985). The agreement is remarkably good, showing that it is plausible to regard the 'disc' component as radiation from interstellar dust in the galaxy illuminated by the general galaxy starlight. Rowan-Robinson and Chester (1986) have estimated that emission from the bulge component identified by Habing et al (1985) would not make a significant contribution to the integrated flux from most galaxies at 12-100 μ . We have also shown an empirical fit to the 'disc' component spectrum of the form $\alpha \nu B_\nu (30K) + \beta \nu B_\nu (210K)$.

Fig 4b shows the spectrum of the 'starburst' component compared with the spectrum of the 3 kpc disc observed in NGC1068 by Telesco et al (1984), with the average spectrum of star-forming clouds in our Galaxy calculated by Rowan-Robinson (1979) and with a simple model for a cloud containing a newly-formed massive star (stellar temperature $T_s = 40000K$, grain condensation temperature $T_1 = 1000\ K$, uniform density, ratio of inner radius of dust cloud, r_1 , to outer radius, r_2 , $r_1/r_2 = 0.0015$, composite interstellar grain properties adopted by Rowan-Robinson (1982), ultraviolet optical depth, $\tau_{UV} = 100$). The latter model is one from a sequence used by Crawford and Rowan-Robinson (1986) for high surface brightness sources in the

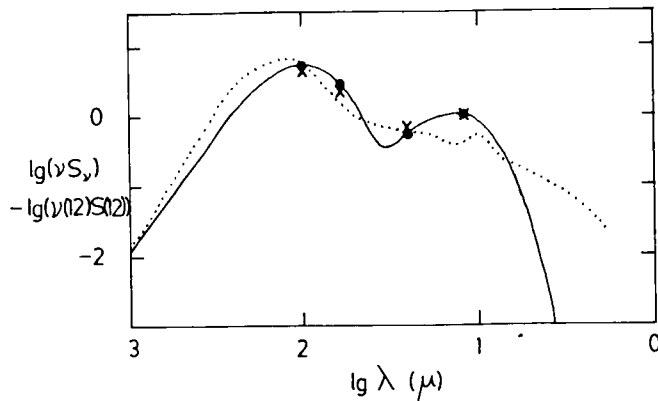
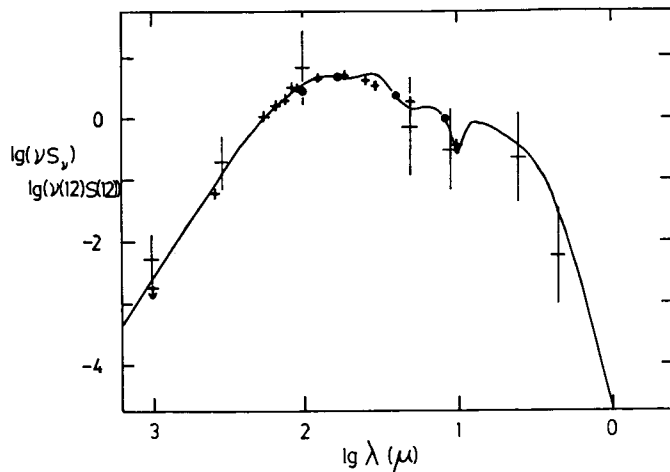
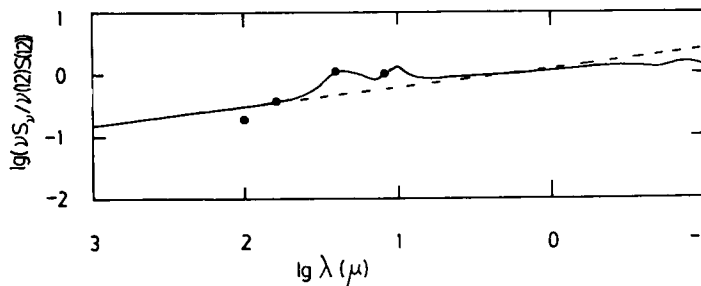


Fig 4 Model fits to the spectra of the adopted components (filled circles). (a) 'disc' component. The x's denote the spectrum of an isolated cirrus cloud in our Galaxy studied by Boulanger et al (1985). The dotted curve is the interstellar grain model of Draine and Anderson (1985). The solid curve is an empirical fit of the form $S_\nu = \alpha \nu B_\nu(30K) + \beta \nu B_\nu(210K)$.



(b) 'starburst' component. The small crosses are the data of Telesco et al (1984) for the 3-kpc ring in NGC 1068, which they attribute to a starburst. The large crosses are the average spectrum for regions of massive star formation in our Galaxy derived by Rowan-Robinson (1979). The solid curve is a simple model for a star-forming region of the type discussed by Crawford and Rowan-Robinson (1986), a uniform spherically symmetric dust cloud illuminated by a hot star ($T_s=40000K$), with optical depth $\tau_{uv} = 100$, ratio of inner to outer cloud radius $r_1/r_2 = 0.0015$.



(c) 'Seyfert' component. The solid curve is a model consisting of an $\alpha = 0.7$ power-law continuum source (indicated by the broken line) embedded in a spherically symmetric dust cloud with density distribution $n(r) \propto r^{-1}$, $r_1 < r < r_2$, optical depth $\tau_{uv} = 1$ ($A_v = 0.23$), temperature of the hottest grains $T_1 = 1000K$, and $r_1/r_2 = 0.0055$.

Galactic plane associated with star-forming regions and compact HII regions.

The agreement of the 'starburst' component spectrum with the model, with the average spectrum for star-forming clouds in our Galaxy, and with the 3 kpc disc in NGC1068 which Telesco et al (1984) argue to be a burst of star formation, is excellent.

Fig 4c compares the spectrum of the 'Seyfert' component with a simple model consisting of a central source with a power-law continuum extending from $\lambda = 0.1 \mu$ to 1 mm embedded in a dust cloud with density distribution $n(r) \propto r^{-1}$, $T_1 = 1000$ k, $r_1/r_2 = 0.0055$, $\tau_{uv} = 1$ ($A_v = 0.23$). The agreement is satisfactory. The spectral index $\alpha = 0.7$ was selected because quasars detected by IRAS appear to have 12 - 100 μ spectral indices centred on this value (Neugebauer, Soifer and Rowan-Robinson 1986). Models with $\alpha = 0.5$, 0.9 also give a reasonable fit. The dust is presumably located in the narrow-line region of the quasar-like object (see section 7). We were not able to obtain a satisfactory fit with $n(r) \propto r^{-2}$ or $n(r) = \text{constant}$.

We conclude that there is a reasonable observational and theoretical basis for the separation into the 3 components of Fig 3 and that this separation may give valuable insight into the nature and energetics of infrared-emitting galaxies.

2.4 Deconvolution into Components

Let $\Delta\nu_i$, $i = 1-4$, be the effective bandwidths for the IRAS 12, 25, 60 and 100 μ bands (i.e. 13.48, 5.16, 2.58 and 1.00×10^{12} Hz respectively, IRAS Explanatory Supplement 1984) and suppose S_i are the fluxes in Jy in each band for a particular galaxy.

$$\text{Let } S_{\text{tot}} = \sum_{i=1}^4 S_i \Delta\nu_i \quad (1)$$

$$\text{and } y_i = S_i / S_{\text{tot}}, \quad i = 1-4. \quad (2)$$

For the 'disc' component ($j = 1$), 'starburst' component ($j = 2$) and 'Seyfert' component ($j = 3$), let the flux in band i be $T_{j,i}$ (Jy) and let

$$T_{j,\text{tot}} = \sum_{i=1}^4 T_{j,i} \Delta\nu_i \quad (3)$$

$$t_{j,i} = T_{j,i} / T_{j,\text{tot}}. \quad (4)$$

We then look for the least-squares solution of the over-determined set of equations

$$y_i = \sum_{j=1}^3 \alpha_j t_{j,i}, \quad i = 1-4, \quad (5)$$

to determine the relative proportions, α_j , $j = 1-3$, of the spectrum attributable to component j . If any of the α_j are found to be negative, the most negative is set to zero and the equations re-solved with one fewer variable. If one of the α_j is still negative, the remaining one is set to be 1.

Table 1 summarizes the number of each mixture combination for each galaxy type. All Seyferts but one have a 'starburst' component and all but 3 have a 'Seyfert' component. The 3 exceptions are all Type 2 Seyferts.

Table 1: Numbers of galaxies with different combinations of 'disc' (D), 'starburst' (B) and 'Seyfert' (S) components

type	number	
D	5	(NGC 2076, 4750, 5078, 5530; 23260-413)
B	5	(NGC 1614, 4418; UGC 8335; 20551-425, 23128-591)
S	1	(IC 4329A)
DB	124	
DBS	51	
DS	7	(NGC 4047, 5656, 7624, 7817; 01091-382, 02069-233, 20243-022)
BS	15	(NGC 1275, 1377, 4253, 5253, 6552; UGC 3426, 4203, 8058, 8850, 9412; 00344-334, 08171-250, 08341-261, 13197-162, 20481-571)

2.5 Correlations Between Luminosities in Components

To calculate the far infrared luminosities in each component we need to apply a correction for the incomplete wavelength coverage of the IRAS bands. Lonsdale et al (1985) have shown that the quantity $1.26(S_3 \Delta\nu_3 + S_4 \Delta\nu_4)$ is an excellent approximation to the 42.5-122.5 μ integrated spectrum of sources with blackbody or powerlaw spectra. The great range of spectral behaviours over the wider range 10-100 μ make it impossible to achieve as good a result over this whole wavelength range. However the quantity

$$1.26 S_{\text{tot}} = 1.26 \sum_{i=1}^4 S_i \Delta\nu_i \quad (6)$$

is a good approximation to the integrated spectrum from 10-120 μ of the 'Seyfert' component model adopted here and is within 15% for the 'starburst' model, so we adopt this as a measure of the 10-120 μ far infrared flux from galaxies.

We have then calculated luminosities in each component, using

$$L_j = 1.26 \alpha_j S_{\text{tot}} .4 \pi d^2 \quad (7)$$

where d is the luminosity distance calculated in an $\Omega = 1$ universe for $H = 50$. We have also calculated optical luminosities based on νS_ν in the B-band applying the de Vaucouleurs et al (1976) internal extinction correction. Corrections for interstellar extinction have been derived from the maps of Burstein and Heiles (1978), assuming $A_B = 4 E(B-V)$. Optical luminosities have not been quoted for galaxies with $b/ < 10^0$ unless direct estimates of interstellar extinction are available.

Fig 5 shows the correlation of L_D , the luminosity in the 'disc' component, with L_{opt} , the B-band optical luminosity, with different galaxy types indicated by different symbols. If the 'disc' component is interpreted as emission from interstellar dust as a result of absorption of starlight, then the ratio of these two luminosities can be interpreted in terms of a characteristic optical depth in dust

$$L_D/L_{opt,tot} \approx (1 - e^{-\tau}) \quad , \quad (8)$$

where $L_{opt,tot} = \int_{opt-uv} L_{\nu} d\nu = 3.3 L_{opt}$ by integration over the interstellar radiation field model of Mathis et al (1983). Lines of constant τ as given by (8) are indicated in Fig 5. As might be expected, early-type galaxies (E and L) have lower values of L_D/L_{opt} , consistent with a low dust content. Any contribution from dust near newly-formed stars or from circumstellar dust shells would also be lower for early-type galaxies. The values of τ are consistent with internal extinction formula of de Vaucouleurs et al (1976). We see that there is no evidence for exceptionally high internal extinction in IRAS galaxies, even where L_{IR}/L_{opt} is exceptionally high. This appears to be in contradiction to the conclusions of Moorwood et al (1986) (and also of de Jong and Brink, see section 3 below). However the corrections for interstellar extinction are very significant for several galaxies in this sample. It is possible that the minisurvey galaxies studied by Moorwood et al lie behind molecular gas associated with the Ophiuchus complex and hence that their interstellar extinction estimates based on neutral hydrogen column density are underestimates.

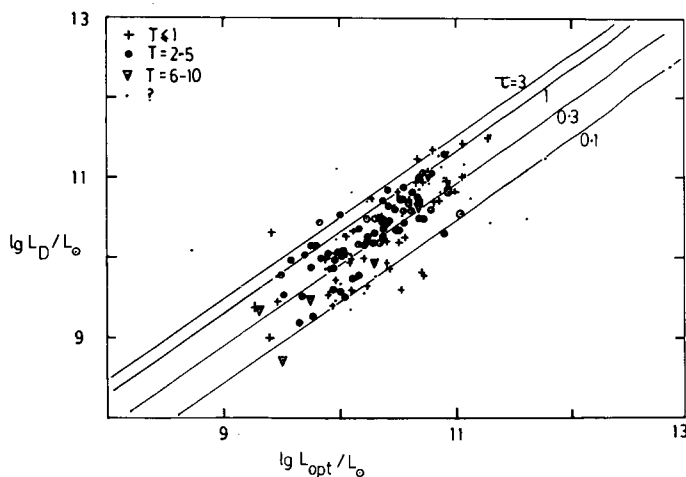


Fig 5 The correlation of the luminosity in the 'disc' component, L_D , in solar units, versus the blue luminosity of the galaxy. $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\Omega_0 = 1$, throughout this paper. Different symbols are used for different ranges of galaxy types, based on the parameter T of de Vaucouleurs et al (1976): + E-S0a, O Sa-Sbc, v Sd-Irr, . type unknown.

The solid lines give values of the characteristic optical depth τ derived from eqn (8).

Fig 6 shows the correlation of L_B , the luminosity in the 'starburst' component with L_{opt} . Here there is a great deal of scatter, consistent with the idea of a transient, high luminosity event. There is clear evidence that barred spiral galaxies have significantly more

luminous starburst components than non-barred spirals and this is the explanation of the correlation of far infrared colour with the presence of a bar, found by Hawarden (1985).

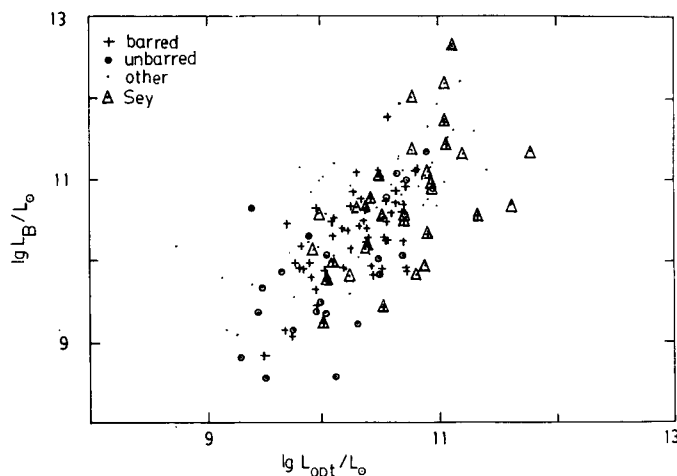


Fig 6 The correlation of the luminosity in the 'starburst' component, L_B , in solar units, versus the blue luminosity of the galaxy. The symbols denote: + barred galaxies (SB or SAB), O un-barred galaxies (SA), . bar-type unknown or not relevant, Δ Seyfert.

A broad correlation is found between L_S , the luminosity in the 'Seyfert' component, and L_B suggesting that there may be a common cause (for example, the sudden feeding of a galactic nucleus with gas) for the starburst and power-law continuum source. Fig 7 shows L_S versus L_X , the X-ray luminosity showing a good correlation, consistent with the idea that the 'Seyfert' component is dust illuminated by the central quasar-like source.

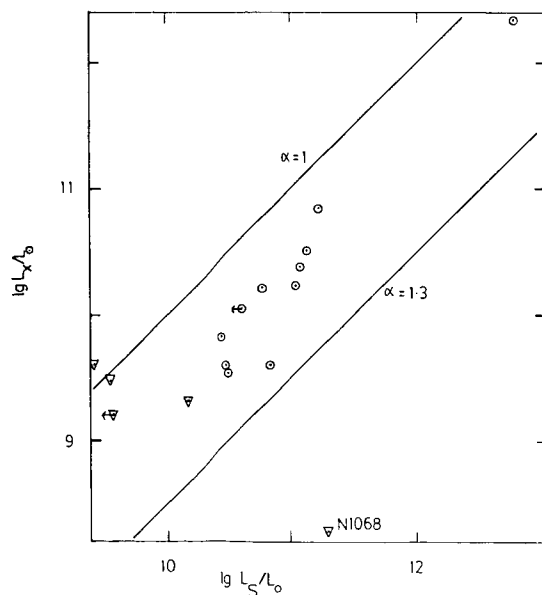


Fig 7 The correlation of the 2-10 keV ('hard') X-ray luminosity, in solar units, with the luminosity in the 'Seyfert' component. Seyferts of type 1 and 2 are denoted by circles and triangles, respectively. The straight lines are labelled with the infrared to X-ray spectral index.

Of the 14 galaxies in our sample which have $L_{IR} > 3.10^{11} L_{\odot}$ the far infrared spectra of 11 are dominated by starburst components (including the galaxy NGC6240 studied by Joseph et al 1984, Becklin et al 1985). The exceptions are the quasar 3C273, the Seyfert 1 galaxy I Zw 1, and the Seyfert 2 galaxy Mk 463.

2.6 Model Fits to the Infrared Spectrum of Selected Galaxies

For several galaxies in our sample the spectra are known at wavelengths outside the 12–100 μ range studied by IRAS, in some cases covering the range from ultraviolet wavelengths to 1 mm. These spectra provide a strong test of our models. The main conclusion of this comparison is that while our models give an excellent fit to the infrared spectra of more than 60% of the galaxies with good spectral data, the remainder require modification to give a good fit in the range 1–10 μ . These cases are almost all Seyfert galaxies and the modification required is that the optical depth across the dust cloud in the narrow-line region should be > 1 .

There are 2 other galaxies which require an additional ingredient to bring their predicted spectra into line with observations. Arp 220 (not actually in our sample) and NGC 4418 both have anomalously high $\{S(25)/S(12)\}$ ratios, most easily understood as due to heavy extinction by interstellar dust in the parent galaxy.

We now discuss these 3 classes of galaxy in turn:

2.6.1. Galaxies for which the models of section 4 are a good fit. Fig 8a,b shows the visible to far infrared spectra of several galaxies for which the basic model of section 4 gives a good fit. These include the galaxy NGC 6240, for which we attribute most of the far infrared emission to a starburst component ($\alpha_2 = 0.95$). The contribution of starlight can be seen at wavelengths shorter than 3 μ (except for NGC 7469, for which it has been subtracted). Fig 8c shows the data for 3C273 compared with our 3-component model and for a model with an additional pure power-law component. Although the latter improves the fit to the IRAS data, the fit to the overall spectrum is not improved. Although we can not resolve the issue of whether dust is present in the emission line region of 3C273, the IRAS data do point to the existence of a starburst in this galaxy.

2.6.2. Galaxies for which a higher optical depth Seyfert component is required. The best observed galaxy in this category is NGC 1068. Fig 8d shows the spectrum of the core (< 100 pc) of this galaxy compared with our standard 'Seyfert' component and with a high optical depth model ($\beta=1$, $T_1=500\text{K}$, $\tau_{\text{UV}}=75$, $r_1/r_2=0.00215$). The latter model, which involves a dust mass of $3 \times 10^5 M_\odot$ distributed between 4 and 180 pc from the central power-law source, is a much better fit to the observations.

On rerunning our deconvolution programme with this higher optical depth Seyfert model, there are several other galaxies for which this gives a much better fit to the overall spectra: NGC 1275, 1386, 3783, 5253 and 6764 and Mrk 3 and 231, illustrated in Fig 8c and e.

2.6.3. Arp 220. Fig 8f shows two possible models for the unusual galaxy Arp 220. This galaxy does not actually qualify for the sample studied in the present paper, since the 12 μ flux is not of sufficient quality, but the interest generated by it (Soifer et al 1984) warrants trying to understand its far infrared spectrum within the framework of the present paper.

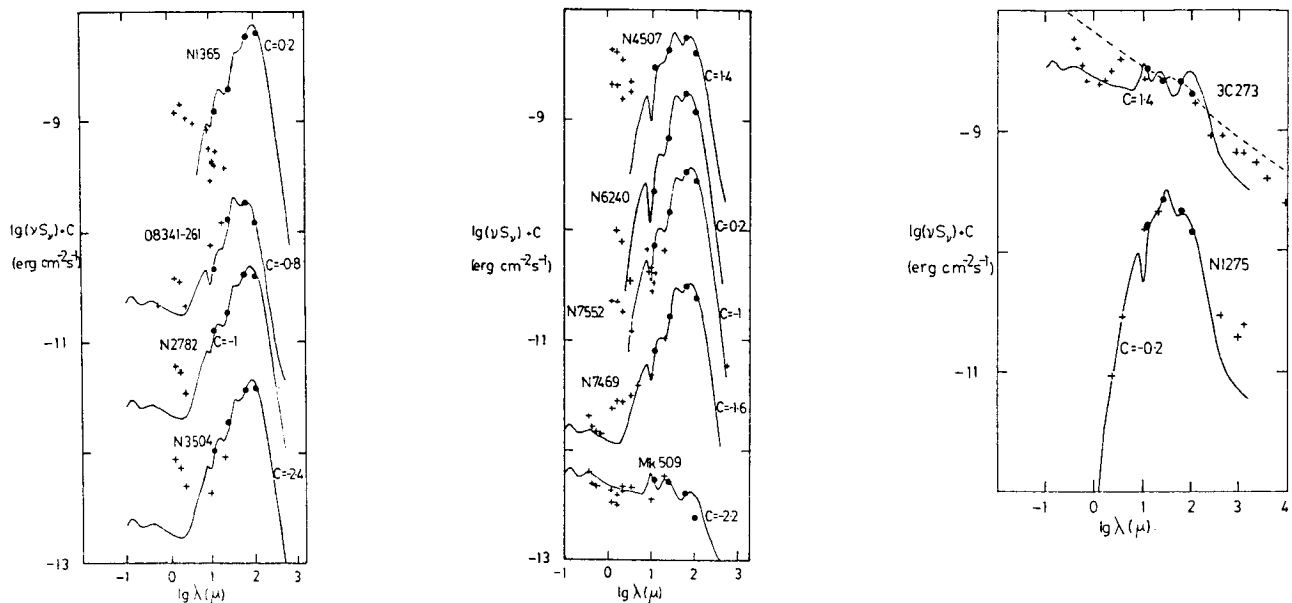


Fig 8 Ultraviolet to millimetre wavelength spectra predicted by the models of the present paper, compared with observations, for selected galaxies. The filled circles are the colour-corrected IRAS data, to which the models were fitted.

(a) NGC 1365, 08341-261, NGC 2782, NGC 3504.

(b) NGC 4507, 6240, 7552, 7469 and Mkn 509.

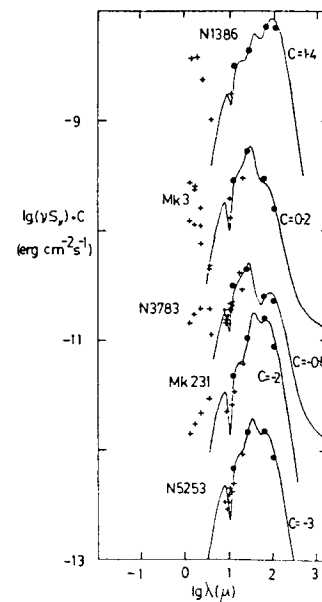
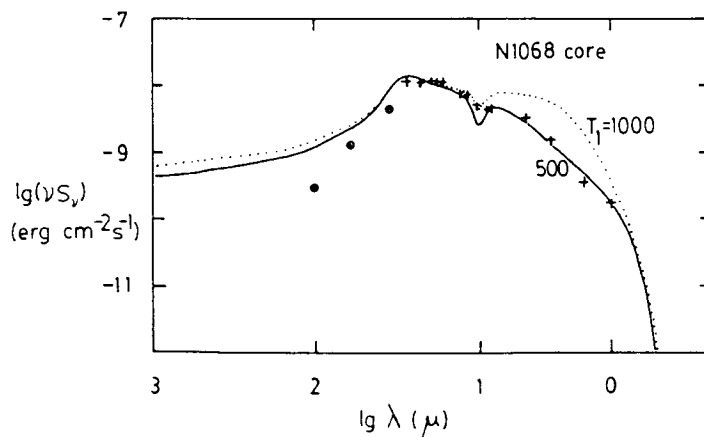
(c) Contemporaneous observations of 3C273 (solid curve: 3-component model, broken curve: 'starburst' plus $\alpha = 0.7$ power-law model) and NGC 1275 ($\tau_{UV}=75$, $T_1=500K$ model, see Fig 8d), the latter with the contribution of starlight subtracted.

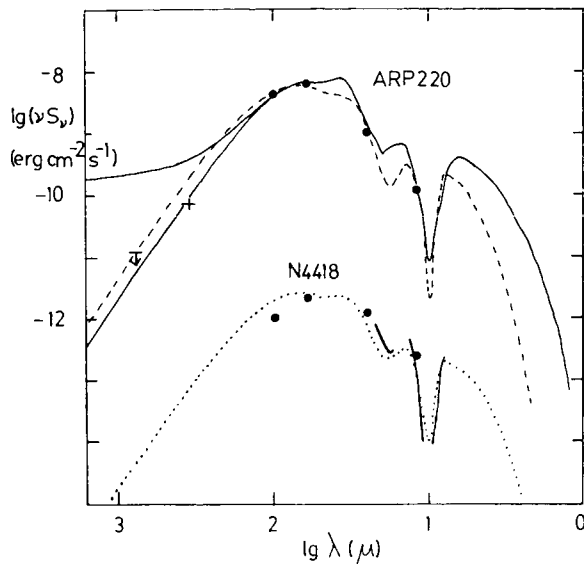
(d) The core of NGC 1068 (data from Telesco et al 1984) compared with $\tau_{UV}=75$ Seyfert model, with $T_1 = 1000K$ (dotted curve) and 500K (solid curve).

(e) Galaxies for which the $\tau_{UV} = 75$,

$T_1 = 500K$ model of Fig 8d gives a better fit to the overall spectrum than our standard model: NGC 1386.

Mkn 3, NGC 3783, Mkn 231, NGC 5253.





(f) Models for Arp 220 (broken curve: 'starburst' model with an additional $A_V = 78$ mag. of extinction by interstellar dust. Solid curve: power-law ($\alpha=0.7$) continuum source embedded in uniform spherically symmetric dust cloud with $\tau_{UV} = 186$ ($A_V=40$). The upper and lower solid curves at larger wavelengths correspond to whether the power-law source continues beyond 100μ or not.) and NGC 4418 (dotted curve: 'starburst' model with an additional $A_V = 39$ mag. of extinction by interstellar dust).

The IRAS colours of this galaxy are unique (for example, $\text{Log}\{S(25)/S(12)\}=1.25$) and it cannot be understood as a mixture of the 3 components used in section 4. It can however be modelled either as a starburst behind very strong ($A_V = 78$ mag.) interstellar extinction (arising perhaps because the galaxy is seen virtually edge-on) or as a quasar embedded in a high optical depth ($\tau_{UV} = 186$, $A_V = 40$) dust cloud. The predicted outer angular radii of the dust clouds are 1.7 for the starburst model with extinction and 0.37 for the embedded quasar model, and since the 20μ emission tends to come from the inner edge of the dust cloud these are both consistent with the $< 1''$ size at 20μ reported by Becklin et al 1986.

2.6.4. NGC 4418. This galaxy has an unusually high $S(25)/S(12)$ ratio and a very deep 10μ absorption feature (Roche et al 1986), both of which suggest exceptionally high extinction. It is located at $l=290$, $b=61$, where the interstellar extinction is low. Our model for this (Fig 8f) consists of a pure starburst model with an additional $A_V=37$ magnitudes of extinction, most of this presumably due to internal extinction in NGC 4418, which would again have to be almost edge-on.

2.7 Discussion

The model fits to the far infrared spectra of the assumed components illustrated in Figure 3 can be used to estimate the dimensions and masses of the dust clouds responsible for the infrared emission. For the 'starburst' and 'Seyfert' component models, which involve a specific optical depth in dust, the angular and linear radius of the dust cloud can be derived from the integrated flux, S_{tot} (eqn (1)) and the luminosity L_j (eqn (7)) respectively.

For the 'starburst' model we find, for a spherically symmetric cloud illuminated by a central cluster of stars,

$$\lg \theta_2(") = -7.83 + 0.5 \lg (1.26 \alpha_2 S_{\text{tot}})$$

and

(9)

$$\lg r_2(\text{cm}) = 14.59 + 0.5 \lg (L_B/L_\odot)$$

The inner edge of the dust cloud is defined by

$$r_1/r_2 = 0.0015.$$

The corresponding dust mass is

$$\lg(M_d/M_\odot) = -6.32 + \lg(L_B/L_\odot). \quad (10)$$

For the galaxies in the present sample, r_2 lies in the range 3 pc to 250 pc, so the starburst activity is confined to a small region of the galaxy, presumably in most cases the nucleus. However our assumption of spherical symmetry clearly underestimates the extent if the stars are distributed through the cloud or if the starburst is actually located in a ring. For example for the NGC 1068 'starburst' component we find $\theta_2 = 3''$ and $r_2 = 30$ pc, considerably smaller than the observed 3 kpc diameter ring.

For the 'Seyfert' model we find

$$\lg \theta_2(") = -7.32 + 0.5 \lg (1.26 \alpha_3 S_{\text{tot}})$$

and

(11)

$$\lg r_2(\text{cm}) = 15.11 + 0.5 \lg(L_S/L_\odot)$$

with a corresponding dust mass

$$\lg(M_D/M_\odot) = -7.81 + \lg(L_S/L_\odot). \quad (12)$$

The inner edge of the dust cloud is defined by

$$r_1/r_2 = 0.0055.$$

For the galaxies in the present sample r_2 lies in the range 30 pc to 400 pc, consistent with the dust being located in the narrow line region of the Seyfert nucleus.

For the 'disc' model we assumed $\tau_\nu \propto \nu$, but the model does not involve any specific value of τ_{uv} so we can only calculate $\tau_{100}^{1/2} \theta_2$, where $\tau_\nu = \tau_{100}(100\mu\text{m}/\lambda)$ is the optical depth in 30K grains. We find

$$\lg \{\tau_{100}^{1/2} r_2(\text{cm})\} = 16.02 + 0.5 \lg(L_D/L_\odot)$$

or

(13)

$$\lg(\tau_{100}^{1/2} e_2(")) = -6.90 + 0.5 \lg \{1.26 \alpha_1 S_{\text{tot}}\}.$$

The optical depth at 12μ in 210 K grains, τ_{12} , is related to that in 30 K grains by $\tau_{12} = 0.98 \times 10^{-4} \tau_{100}$. For a source to be a point source at 60 and 100μ , the full width at half-power cannot be greater than $1'$. Galaxies with $\alpha_D > 0.5$ yield $\tau_{100}^{1/2} e_2(")$ in the range 0.6 to 1.2 and this implies $\tau_{100} > 0.0004$. Using the interstellar grain model of Rowan-Robinson (1986), we can translate this lower limit on τ_{100} to one on A_V and find $A_V > 0.8$. This is broadly consistent with the optical depth estimates derived from Fig 5. As many of the galaxies in the present sample have Holmberg diameters considerably greater than $1'$, we must presume that the bulk of the far infrared emission comes from the inner part of the galaxy. This is still consistent with being reemission of starlight obscured by interstellar dust, since the halfpower width of the optical light is much smaller than the Holmberg diameter.

3. THE DE JONG AND BRINK STUDY

de Jong and Brink decompose the far infrared energy distribution into two $Q_\nu B_\nu(T)$ components with $Q_\nu \propto \nu$ and the dust temperatures $T = 15, 60$ K.

The warm component is heated by recently formed stars ($T_g=30000$ K) inside molecular clouds. 50% of the luminosity of these stars is assumed to be absorbed inside the clouds and 50% is assumed to escape and contribute to the cool component.

The cool component is heated partly by older disk stars ($T_g=7000$ K) in the general interstellar medium and partly by light from recently formed stars which escapes from the molecular clouds where the stars have formed.

They solve for A_B^0 , the face-on extinction, L_1 , the luminosity of the disk stars, and L_2 , the luminosity of recently born stars, such that the IRAS 60 and 100μ fluxes and the observed blue magnitude are reproduced. The calculation takes account of the inclination of the galaxy and the λ^{-1} dependence of extinction (so there are different optical depths for 30000 and 7000 K radiation). The analysis has been applied to two samples: a representative sample of 120 galaxies from the Revised Shapley Ames Catalog, and a subset of 20 minisurvey galaxies studied in detail by Moorwood et al (1986).

de Jong and Brink conclude that:

(i) A large fraction of the disk infrared luminosity is emitted at wavelengths $>100 \mu\text{m}$.

(ii) For the RSA galaxies the values of A_B^0 and their dependence on galaxy type agree well (within a factor of two) with those derived from optical data by Sandage and Tammann (1981) and by de Vaucouleurs et al (1976). Their Fig 1 gives the average value of A_B^0 for each Hubble type.

(iii) The minisurvey galaxies show enhanced star formation (higher values of L_2/L_1), higher values of A_B^0 (50% of the sample have $A_B^0 > 1$, compared with 9% for the RSA sample), and a tendency to be more highly inclined (40% of the sample have $a/b > 2.5$ compared with 15% for the RSA sample). The minisurvey sample can be subdivided into 40% which are highly inclined normal galaxies and 60% which have ~ 3 times larger star formation rates. Galaxies in the latter group are about twice as dusty as normal galaxies.

(iv) The model gives a natural explanation of the distribution of galaxies in the L_{IR}/L_{BT} versus $S(100)/S(60)$ diagram.

4. THE HELOU STUDY

The sample studied by Helou consists of all galaxies in 'Catalogued Galaxies and Quasars Observed in the IRAS Survey' (Lonsdale et al 1985) having high quality fluxes in all four IRAS bands and not flagged as extended. Most galaxies with $S(60)/S(25) < 5.5$ are Seyferts (de Grijp et al 1985) and are not considered further by Helou. Fig 9a shows $S(60)/S(100)$ versus $S(12)/S(25)$ for 'normal' galaxies (those with $S(60)/S(25) > 5.5$). They spread out along a band such that the warmer they are in $S(12)/S(25)$, the cooler they are in $S(60)/S(100)$.

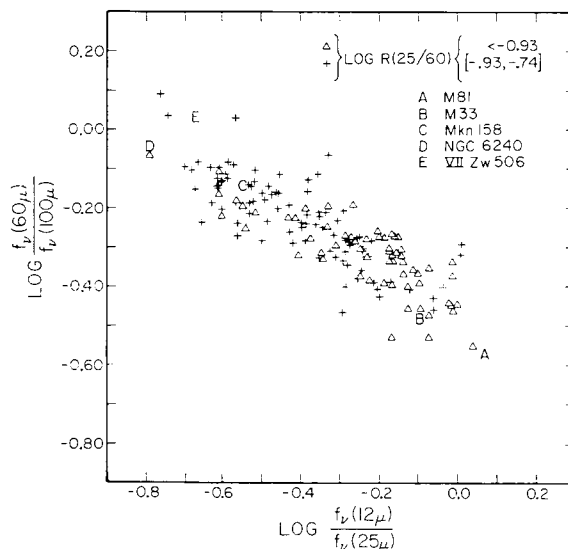
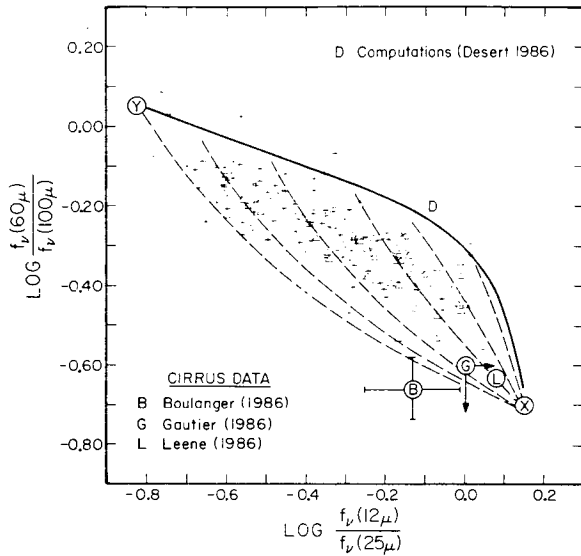


Fig 9 (a) The IRAS colour-colour diagram for 'normal' galaxies, with a few galaxies identified by letters.

The band corresponds to progressively greater star formation activity as it proceeds from the lower right hand corner to the upper left hand corner of the diagram. Galactic cirrus (Low et al 1984, Gautier 1986, Leene 1986) is found at the lower end of the band, together with very quiescent spirals such as M31 and M81. In contrast the upper end of the band is occupied by starburst galaxies like NGC 6240 (Wright, Joseph & Meikle 1984) and blue compact galaxies or 'extragalactic HII regions' such as Mrk 158, and compact Zwicky galaxies (Kunth and Sevre 1986, Wynn-Williams and Becklin 1986). This interpretation is supported by a model in which a realistic

mixture of grains including polycyclic aromatic hydrocarbons (PAH) is subjected to increasingly intense radiation fields (Desert 1986: see the curve labelled D in Fig 9b).



(b) As above, compared to the model by Helou. Various cirrus measurements are shown.

Two other samples of IRAS galaxies confirm the reality of the band in Fig 9: a sample of Virgo cluster spirals complete to $B = 12.8$ (Helou 1986), and a sample of near-by galaxies, roughly complete to an apparent diameter of $10'$ (Rice et al 1986). However the restriction to unresolved galaxies in the Helou and Rowan-Robinson and Crawford studies does lead to underpopulation of the low surface brightness, cooler (in $S(60)/S(100)$) end of the band.

Helou argues that the spread across the band implies that a simple mixing of two fixed components, C ('cirrus') and A (active component related to HII regions) is inadequate. He argues that two physical parameters are required to characterize the distribution: the intensity in its active regions, A, and the ratio A/C, where C is the (fixed) cirrus component. As the ambient radiation field goes from solar neighbourhood intensity to several hundred times this value, A traces out the curve D in Fig 9b from X to Y. As this is an upper envelope to the observed band the model is capable of explaining all galaxy colours.

The C component is due in large part to older disk stars and cannot be identified with recent star formation. The close relation between non-thermal radio and far infrared emission becomes even more intriguing, as it seems to apply independent of IRAS colour (Helou, Soifer and Rowan-Robinson 1985).

5. DISCUSSION

These 3 models for the observed normal galaxy - starburst sequence are strikingly different in their predictions of the optical properties of IRAS galaxies. In the Rowan-Robinson and Crawford model, the

starburst component is immersed in over 50 magnitudes of visual extinction, so there would be virtually no additional radiation observed in the visible. de Jong and Brink allow 50% of the radiation from the starburst to escape, so that IRAS galaxies with strong starbursts should differ in colour and intensity profile from normal galaxies. Helou's calculation (curve D in Fig 9b) is essentially an optically thin one, so would imply drastic changes to the visible appearance of a strong IRAS starburst galaxy. However Helou (1986a) argues that the dust optical depth must in fact increase for strong starburst galaxies because of the high value of $L_{\text{IR}}/L_{\text{opt}}$. Further study is needed to establish whether the presence of a strong, warm component at 60 and 100 μ is accompanied by changes in the visible appearance of the galaxy. My impression of the work published to date is that there is in general no drastic change. A preliminary look at the distribution of $L_{\text{D}}/L_{\text{opt}}$ versus $L_{\text{B}}/L_{\text{opt}}$ in the model of Rowan-Robinson and Crawford shows no evidence of the strong correlation that would be expected in the de Jong and Brink model.

The question raised by de Jong and Brink as to whether galaxies with high values of infrared-to-optical luminosity ratio also have abnormally high internal extinction deserves further study, as also does the question of whether edge-on-galaxies are over-represented (de Jong and Brink) or under-represented (Burstein 1986) in the IRAS survey. My own recommendation is that these studies should not be carried out on the minisurvey sample, much of which lies near the Ophiucus and Taurus molecular clouds, where the magnitude of interstellar extinction in our own Galaxy cannot be reliably estimated. Finally it is clear that the current star formation rate in a galaxy can not be calculated simply by multiplying the far infrared luminosity by an appropriate constant.

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DISCUSSION *

PUGET:

If you consider the cirrus component in our Galaxy, about half of the heating is due to UV coming from B stars, so that component is related to star formation.

HELOU:

Yes, but it is difficult to deduce the amount of star formation from the infrared emission, because of the uncertain fraction of B star luminosity that is being re-radiated by the cirrus. The point of all this is that the relation between total infrared emission and massive star formation rate in a galaxy is not linear, but must depend on the IRAS colors.

de JONG:

I would like to react to a question that has been raised by several people this morning concerning the correlation between the far-infrared and the radio continuum emission of galaxies. The fact that not only the $60\mu\text{m}$ but also the $100\mu\text{m}$ fluxes correlate extremely well with the radio continuum flux indicates that a substantial fraction of the recently formed stars have moved out of the molecular cloud in which they were born, within their lifetime. These stars contribute significantly to the general interstellar radiation field that is supposed to heat the cool dust responsible for the $100\mu\text{m}$ emission. In our simple two-component galaxy model, presented at this meeting, this has been taken into account.

YOUNG:

On the one hand, the tight correlation between L_{IR} and radio continuum is not surprising, since within individual galaxies the continuum resembles the $\text{H}\alpha$, CO and blue light. On the other hand, I find it puzzling that the L_{IR} is so tightly correlated given that it depends on the 5th power of T_{dust} .

HELOU:

The scaling with T_{dust} is in this case an irrelevant truth, because what determines L_{IR} in the end is the amount of heating luminosity available. The reason I find the correlation puzzling is the long chain of intervening steps between L_{IR} and $L_{1.4\text{GHz}}$. On one hand, you heat dust grains with the starlight, on the other, you wait for the stars to go supernova and produce cosmic ray electrons, then take those and put them in the magnetic field to radiate. There must be a dozen free parameters, and yet the ratio $L_{\text{IR}}/L_{1.4\text{GHz}}$ is constant!

* Note: The paper was read by G. Helou.