THE FAR INFRARED VIEW OF STAR FORMATION IN GALAXIES

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ABSTRACT: The contributions to the far infrared spectra of galaxies of the 'cool' cirrus and 'warm' starburst components are reviewed, together with the complications introduced by dust in the narrow-line regions of Seyferts, the destruction of very small grains, and the small percentage of galaxies which are optically thick in the optical band. The role of interactions and mergers in generating ultraluminous infrared galaxies is reviewed.

1. INTRODUCTION

It is in the far infrared that we get a true picture of the amount of star formation in galaxies. The view from the visible or near infrared is a very partial one because, as I shall argue, most massive star formation takes place within highly optically thick clouds of dust and molecules, with a typical A_V of 20.

In section 2 I discuss the 'cool' component of far infrared emission from spiral galaxies, the infrared cirrus, which is due to reemission of absorbed starlight by interstellar dust. I argue that the typical optical depth perpendicular to the disc is low for the vast majority of galaxies and hence that Disney's hypothesis of optically thick spiral discs is untenable for most galaxies.

Section 3 deals with the 'warm' component of far infrared emission peaking at about 60 μm, which I argue is due to regions of massive star formation. Several lines of evidence point to a high typical optical depth of these regions at visible and ultraviolet wavelengths. However other evidence suggests that there are directions in which ultraviolet radiation escapes from star-forming regions and hence that non-spherically symmetric models must be considered.

In section 4 I discuss some of the complications of the above simple 2-component decomposition of far infrared spectra: the presence of a component peaking at 25 μm in Seyfert galaxies, probably due to emission from dust in the narrow-line region; the destruction of very small grains at high ultraviolet radiation intensities; and galaxies with unusual spectra. Finally in section 5 I review the evidence for the role of interactions and mergers in generating ultraluminous infrared galaxies.

A more detailed review of some of the material of scetions 2-4, and of interstellar dust

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in galaxies in general, is given in Rowan-Robinson (1990, RR90).

2. THE 'COOL' COMPONENT OF FAR INFRARED EMISSION

If we look around our Galaxy at 100 μm, then in most directions we see cool emission from interstellar dust. This is merely the reradiated interstellar radiation field and it tells us nothing about star formation, only something about interstellar dust. Associated with the emission peaking at 100 μm there is the characteristic signature of the out-of-equilibrium radiation from very small grains or large molecules, continuum emission peaking at 10 μm and the broad 'unidentified' infrared emission features.

Figure 1, taken from RR90 summarises the available information on the emissivity of our Galaxy towards the Galactic poles and towards the central regions of the Galaxy, compared with the predictions of a new composite model for interstellar grains. The agreement is satisfactory. Note that the IRAS data points at 60 and 100 μm may have to be lowered by about 0.2-0.25 dex in the light of the COBE results (Mather et al 1990).

This cool component can be identified and separated out in other galaxies if we have 10-100 μm observations (and ideally, observations to 800 μm). Such a separation was carried out by Rowan-Robinson and Crawford (1989, RRC). Fig 2, taken from the latter paper, shows a comparison of the total luminosity in the cool component with the blue-band luminosity of the galaxy for unresolved IRAS galaxies detected in all 4 IRAS bands, excluding Seyferts. The ratio of these two luminosities can be interpreted as a characteristic interstellar extinction optical depth in the ultraviolet. The results agree surprisingly well with the estimates derived from galaxy photometry by de Vaucouleurs et al (1976). Less than 10 % of galaxies have anomalously large $A_{V,is}$. Disney et al's (1989) hypothesis of an optically thick disk of dust in most spiral galaxies is simply untenable. Valentijn (1990) has suggested that the discs of spirals, including our own Galaxy, could be optically thick due to a dust component distinct from that responsible for the cirrus emission, for example associated with a new population of compact molecular clouds. However this is inconsistent with the fact that in our Galaxy there is a good correlation between interstellar reddening and HI column-density (Burstein and Heiles 1978), and between HI column-density and 100 μm intensity outside known molecular clouds (Boulanger and Perault 1988, Rowan-Robinson et al 1990a).

3. THE 'WARM' COMPONENT OF FAR INFRARED EMISSION

There are a few directions in our Galaxy where, in the far infrared, we see clear evidence of active formation of massive stars. These are mostly confined to within 1 or 2 degrees of the Galactic plane or to a few prominent molecular clouds out of the plane (eg Orion, Ophiuchus). These star formation regions also have a characteristic far infrared spectrum peaking at about 50 μm and falling away sharply towards 10 μm. In the 1-10 μm band the spectrum depends strongly on the geometry and orientation of the source. Spherically symmetric geometry is unlikely to hold except in the very early stages of formation of a massive star. But the main impact of these geometrical effects is

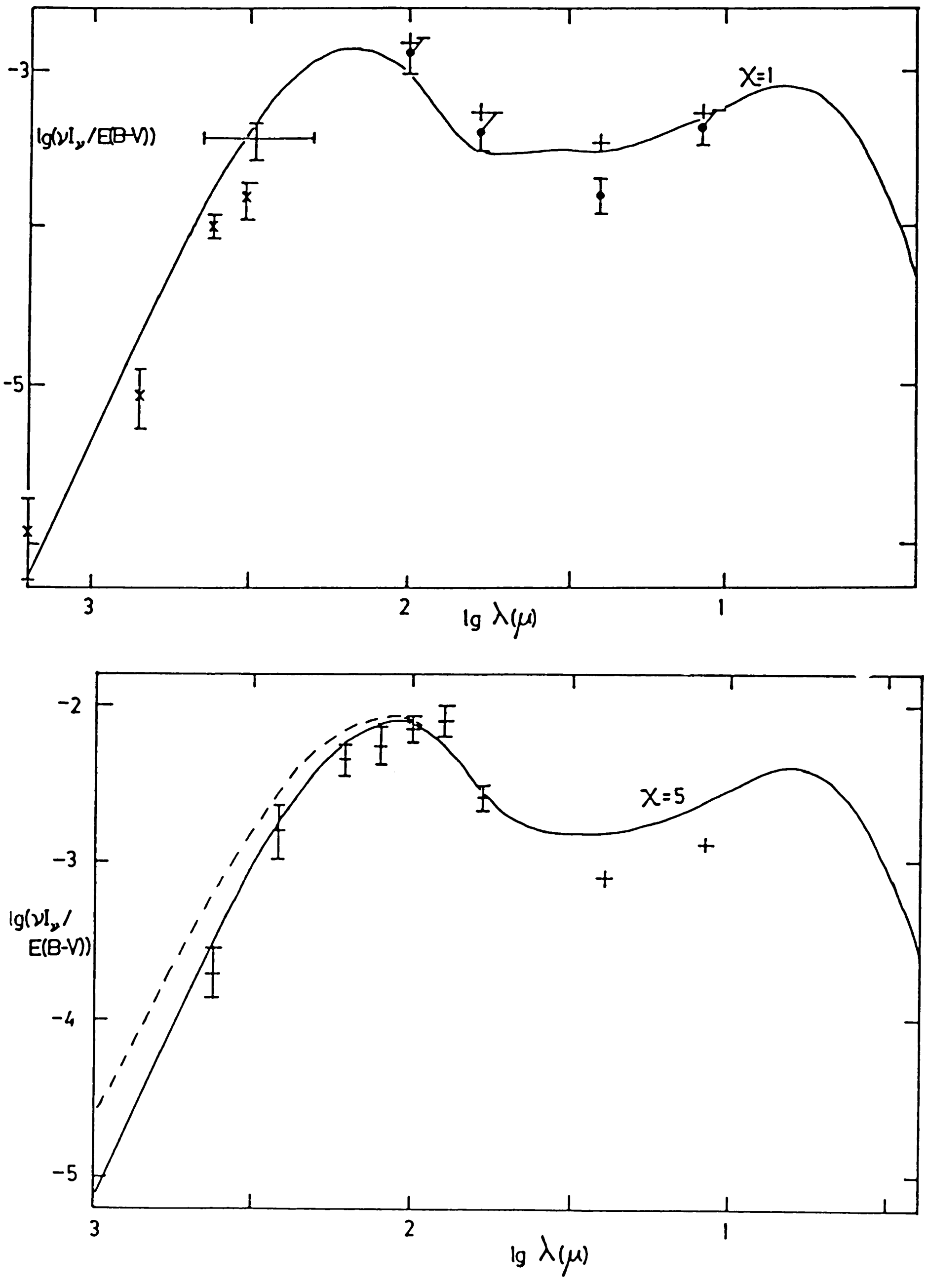

Fig 1: Predicted emissivity, compared with observations towards the Galactic pole (top) and the central regions of the Galaxy (bottom) (from Rowan-Robinson 1990).

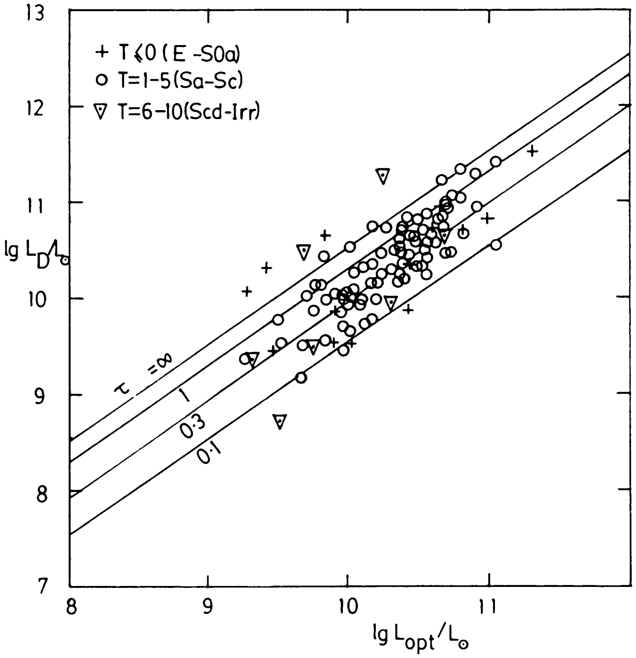

Fig 2: The correlation of the luminosity in the 'cool', cirrus component with the blue-band luminosity of the galaxy (corrected for internal absoprtion), for unresolved IRAS galaxies with data in all four bands, excluding Seyferts. Most galaxies are consistent with being optically thin to interstellar dust. From Rowan-Robinson and Crawford (1989).

at wavelengths shortwards of 10 μm (Efstathiou and Rowan-Robinson 1990). Models for these massive star-forming regions in our Galaxy require high optical depth, with $A_V \approx 20$ (Crawford and Rowan-Robinson 1986), consistent with the known optical depth of the molecular clouds.

External galaxies in which the warm component dominates also require a high optical depth model to fit their far infrared spectrum (RRC). Other evidence for a high optical depth to the newly forming stars comes from the observed ratios of Brackett α to Brackett γ in selected starburst galaxies, which imply A_V = 7-33 (Kawara et al 1988), and the very high values of $L_{fir}/L_{H\alpha}$, 200-4000, found by Leech et al (1988) for starburst galaxies compared with values of 30-100 found for nearby normal galaxies by Persson and Helou (1987). However a hot star surrounded by a spherically symmetric cloud with $A_V = 20$, would generate negligible Hα emission, contradicting the clear evidence for emission line activity seen in starburst galaxies in the optical band. Also the observed ratios of Hα/Hβ correspond to $A_V \approx$ 1-3 (Leech et al 1988,1989). The simplest explanation of these disparate pieces of evidence is that the global geometry of starburst nuclei, or the geometry of individual star-forming regions, is non-spherical and that some fraction (≈10%) of the optical and ultraviolet light from the young massive stars escapes. Axially symmetric models for starburst nuclei have been investigated by Efstathiou and Rowan-Robinson (1990). The geometry and orientation have a big effect on the 1-10 μm spectrum, but rather little effect in the far infrared.

Thus we are able to identify the active star-formation component in external galaxies from the 10-100 μm spectra. As we might expect, this component shows a much greater range in the ratio of its luminosity to the blue-band luminosity of the galaxy than does the cool component (RRC). In fact the ratio L_{sb}/L_{opt} has a range of at least 600 (Fig 3). The ratio increases from Hubble type Sc to S0a (Devereux 1987, RRC), and is higher for barred than unbarred spirals (Hawarden et al 1987, Dressel 1990). At low values of this ratio the star formation is spread over the whole galaxy (though concentrated to spiral arms, of course). At high values, $L_{sb}/L_{opt} > 3$ say, i.e. starburst galaxies, star formation tends to be concentrated to the nucleus of the galaxy, the morphology is increasingly that of interactions or mergers (see section 5 below) and there is an increasing ratio of molecular to atomic gas and of L_{fir} to M_{gas} (Mirabel and Sanders 1989). These trends are summarised in Fig 4, taken from the latter reference.

The deconvolution of the far infrared spectra of galaxies into cool and warm components is greatly aided if observations at 300-800 μm are available (RR90). Fig 5 shows models for spectra of 7 galaxies mapped at 800 μm by Rowan-Robinson et al (1990b), taken from RR90.

4. SOME COMPLICATIONS OF THE 2-COMPONENT MODEL

Although the simple deconvolution described above into cool cirrus and warm starburst components works for 90 % of IRAS galaxies, there are several additional factors which need to be considered to model the full range of infrared galaxy properties seen by IRAS.

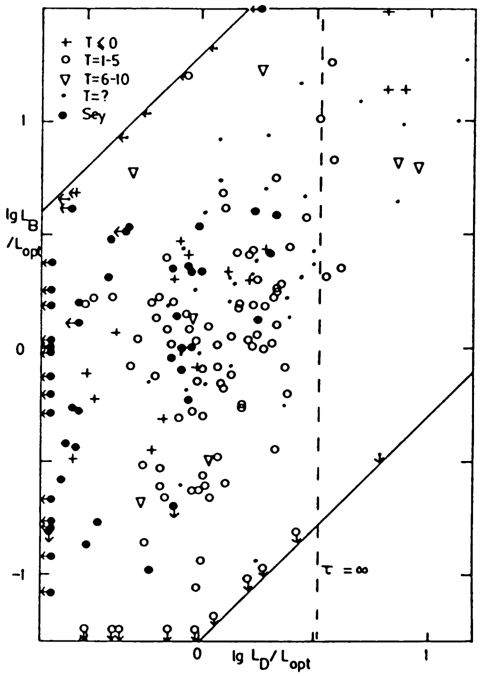

Fig 3: Ratio of infrared luminosity in starburst component to optical luminosity, versus ratio of infrared luminosity in cirrus component to optical luminosity for unresolved IRAS galaxies (Rowan-Robinson and Crawford 1989). Many of the Seyferts (filled circles) are deficient in the cirrus component.

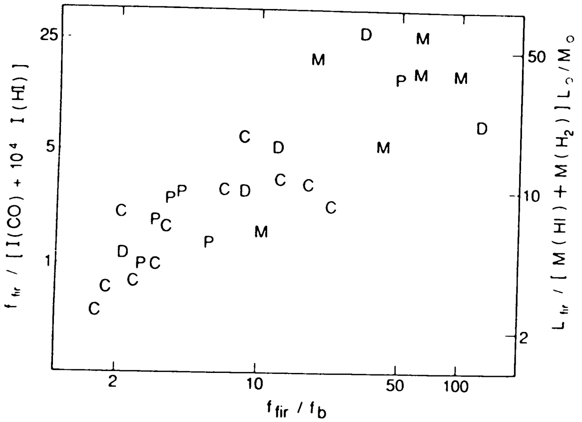

Fig 4: Morphology of IRAS galaxies in a plot of infrared emissivity per unit column of gas versus ratio of infrared to blue-band flux. C = companion at 0.5-2 galaxy diameters, P = companion at < 0.5 galaxy diameter. D = single tidally distorted disk. M = advanced merger. From Mirabel and Sanders (1989).

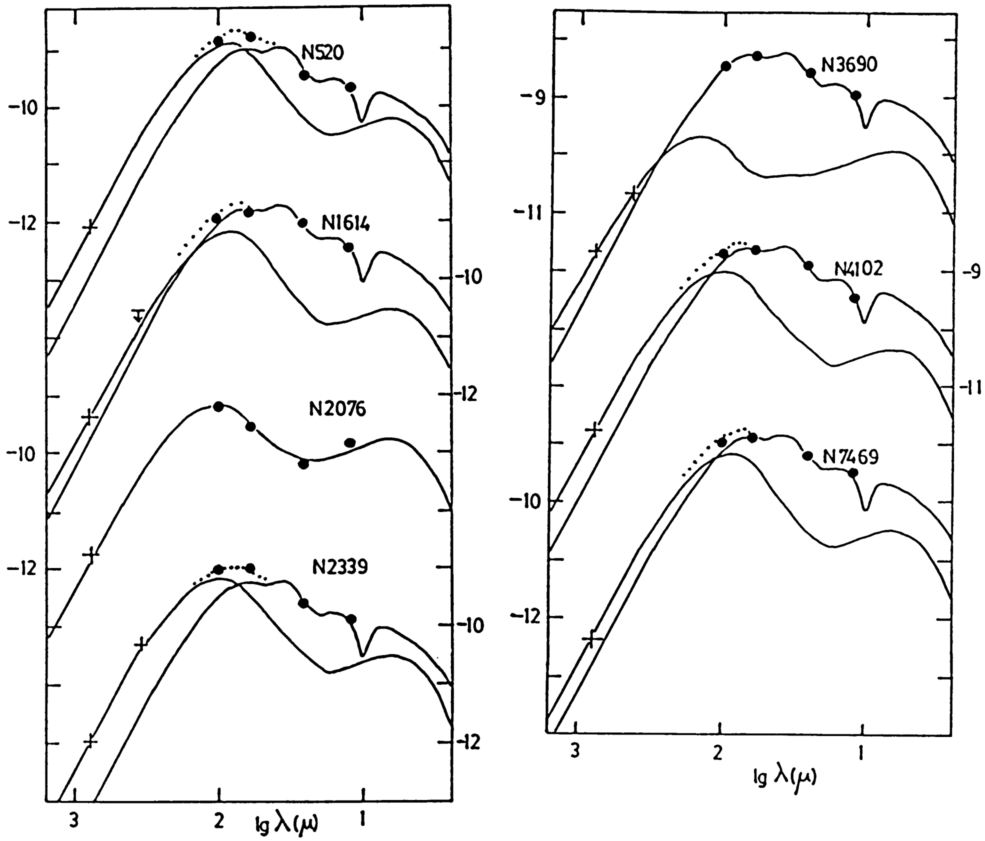

Fig 5: Far infrared and submillimetre spectra of galaxies mapped by Rowan-Robinson et al (1990) at 800 μm, compared with models of RR90. For NGC 2076 a pure cirrus model, with depletion of smallest grains, is satisfactory. For the other galaxies both cirrus and starburst components are required. From Rowan-Robinson (1990).

(1) Seyfert galaxies tend to have an additional component in their spectrum peaking at 25 μm (Miley et al 1983). This has been modelled by RRC as dust in the narrow-line region of the Seyfert nucleus, with an $n(r) \propto r^{-1}$ density distribution. More sophisticated models with axially symmetric geometry have been developed by Efstathiou and Rowan-Robinson (1990) and these are more successful at fitting the 1-10 μm spectra of Seyferts.

(2) There is a range of interstellar radiation field intensities within a galaxy (see eg Fig 1) and this will result in different emission spectra from different parts of the galaxy. Only for very nearby galaxies can we hope to study this variation at present. For external galaxies we have to make do with an average intensity and corresponding cirrus spectrum. However this average intensity clearly differs from galaxy to galaxy. Figs 6 a-d show the IRAS colour-colour diagrams for two samples of IRAS galaxies compared with the predictions of the cirrus model described in RR90, which incorporates the interstellar radiation field intensity as a parameter.

(3) The very small grain component responsible for the 3-30 μm cirrus emission is destroyed at high ultraviolet radiation intensities (Roche 1988, Desert and Dennefeld 1988, Boulanger et al 1988). This is the explanation of the very weak cirrus components found by RRC in some Seyferts (see Fig 3). Galaxies to the right of the solid curve in Fig 6d are also candidates for small grain destruction. The SMC is one of the best examples of galaxies with a deficit of very small grains (Schwering 1988), though this may be due to the very low heavy element abundance in the SMC rather than to small grain destruction (RR90). Telesco et al (1989) also argue that the spatial variation of mid-infrared colours in the central region of M82 implies small grain destruction.

(4) There are several nearby galaxies which have unusually strong 12 μm emission, of which M31 is the archetype. The explanation for this is unclear at present, though an unusually large abundance of the very smallest grains is probably the best bet (RR90).

(5) There are 3 galaxies whose spectra are consistent with starbursts seen through tens of magnitudes of additional extinction, perhaps due to an edge-on perspective: Arp 220, NGC 4418 and NGC 1569 (RRC, RR90, see also Fig 6a,c). From the spectra alone the hypothesis of a quasar buried in dust can also not be ruled out.

(6) Finally, about 5% of the galaxies studied by RRC have $L_{cool}/L_{opt} > 3$ (see Fig 1 and 3), ie the cirrus emission exceeds the total optical and ultraviolet emission from the galaxy corrected for internal absorption according to the de Vaucouleurs et al (1976) formula. The implication here is that the internal absorption has been underestimated and probably $A_{V,int} >> 1$. Moorwood et al (1986) and Disney et al (1989) have argued that this is the case for the majority of IRAS galaxies, but the evidence presented in this review shows that these galaxies are a small subset of all IRAS galaxies. There is only one galaxy with $L_{ir} > 10^{12}\ L_o$ in this category, UGC5101. Contrary to the arguments of Thronson et al (1990), NGC6240 does not belong in this category. The RRC model for this galaxy has $L_{cool}/L_{opt} = 1.9$, consistent with $A_{V,int} \approx 1$, but $L_{cool}/L_{ir} = 0.1$, so only a small part of the far infrared luminosity is contributed by the cirrus component.

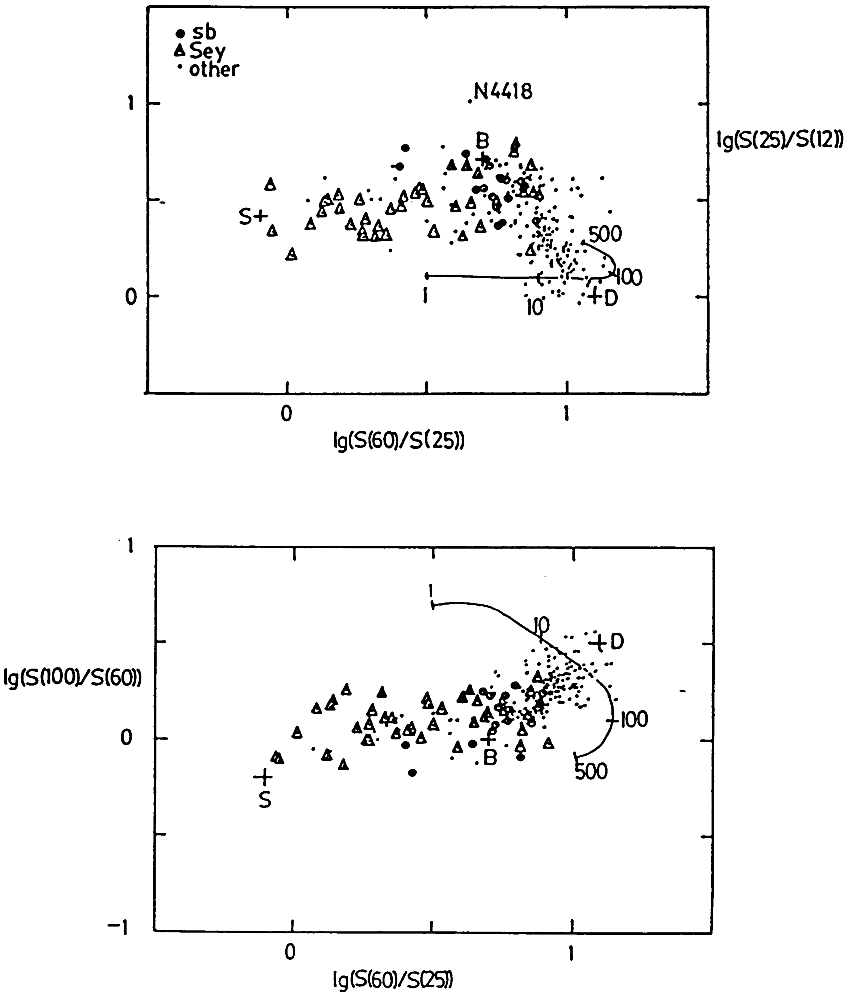

Fig 6a,b: Predicted IRAS colour-colour diagrams for dust models of RR90 compared with data for unresolved IRAS galaxies with good quality fluxes in all 4 bands from Rowan-Robinson and Crawford (1989). S, B denote the locations of Seyfert and starburst components. The curved lines denote the cirrus models of RR90, with varying intensity of the interstellar radiation field.

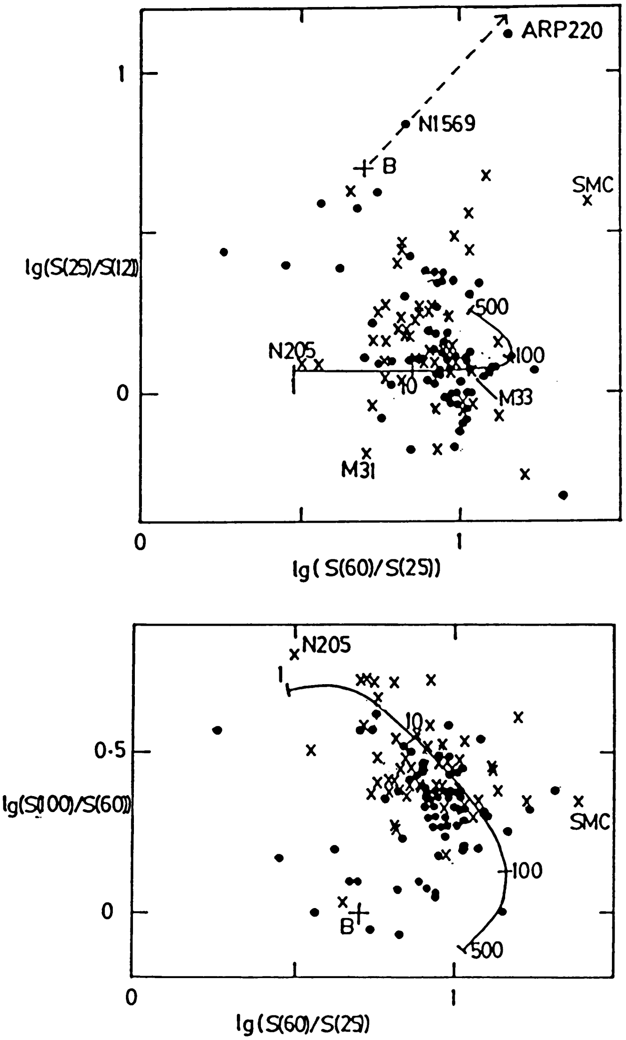

Fig 6 c,d: Data for resolved IRAS galaxies with coadded fluxes in all four bands (RR90 and references therein). The broken curve in Fig 6c shows the effect of reddening (A_V = 40) on the starburst component.

Also L_{sb}/L_{opt} = 17 so this is a very strong starburst galaxy, according to the deconvolution of RRC. If the very small grains in NGC6240 have been depleted, a larger contribution to L_{ir} from the cool component could be accomodated, up to 25%, and this would give better consistency with the observations of Keel (1990a).

5. THE ROLE OF INTERACTIONS AND MERGERS IN ULTRALUMINOUS INFRARED GALAXIES

Perhaps the most interesting infrared discovery to date, from the point of view of the dynamics of galaxies, is that interactions and mergers play a strong, perhaps dominent role in the generation of ultraluminous infrared galaxies. Although there has been controversy about how dominant this role is, I believe we are now close to a resolution of this.

Evidence that interacting galaxies were in some sense more 'active' was given by Stocke (1978) and Hummel (1981) for radio emission, by Larson and Tinsley (1978) for uv excess, by Joseph et al (1984a) and Joseph and Wright (1985) for near infrared excess, by Lonsdale et al (1984) and Cutri and McAlary (1985) for mid infrared excess, and by Kennicut and Keel (1984) and Keel et al (1985) for emission line strength. In most cases, however, this enhanced activity is a statistical effect, at the 10-20% level (see the review by Keel 1990b).

Evidence that infrared-luminous galaxies are interacting or merging was given by Wright et al (1984), Joseph et al (1984b), Soifer et al (1984), Allen et al (1985), Sanders et al (1986), Armus et al (1987) and Telesco et al (1988). Sanders et al (1988) found that all ten galaxies with $L_{ir} > 10^{12}\ L_o$ in the 5 Jy sample have morphological peculiarities. On the other hand Lawrence et al (1989) studied 60 high luminosity IRAS galaxies and an optically selected control sample of 87 galaxies and found that the proportion of interacting, merging or peculiar galaxies was as follows:

sample	% interacting, merging or peculiar
control	18 ± 5 %
IRAS, $L_{60} < 10^{11}\ L_o$	11 ± 8 %
IRAS, $L_{60} > 10^{11}\ L_o$	46 ± 12 %
IRAS, $L_{60} > 3.10^{11}\ L_o$	46 ± 20 %

apparently in conflict with Sanders et al. The discrepancy is not due to the different definitions of L_{ir} and different Hubble constants used in the 2 studies. A typical starburst galaxy with a νL_ν luminosity at 60 μm, $L_{60} = 10^{12}\ L_o$, in the H_o = 50 model used by Lawrence et al (1989), would have an 8-1000 μm luminosity, L_{ir}, close to 10^{12} in the H_o = 75 model used by Sanders et al. Melnick and Mirabel (1990) imaged 15 new $L_{ir} > 10^{12}\ L_o$ IRAS galaxies from the 5 Jy sample with the ESO New Technology

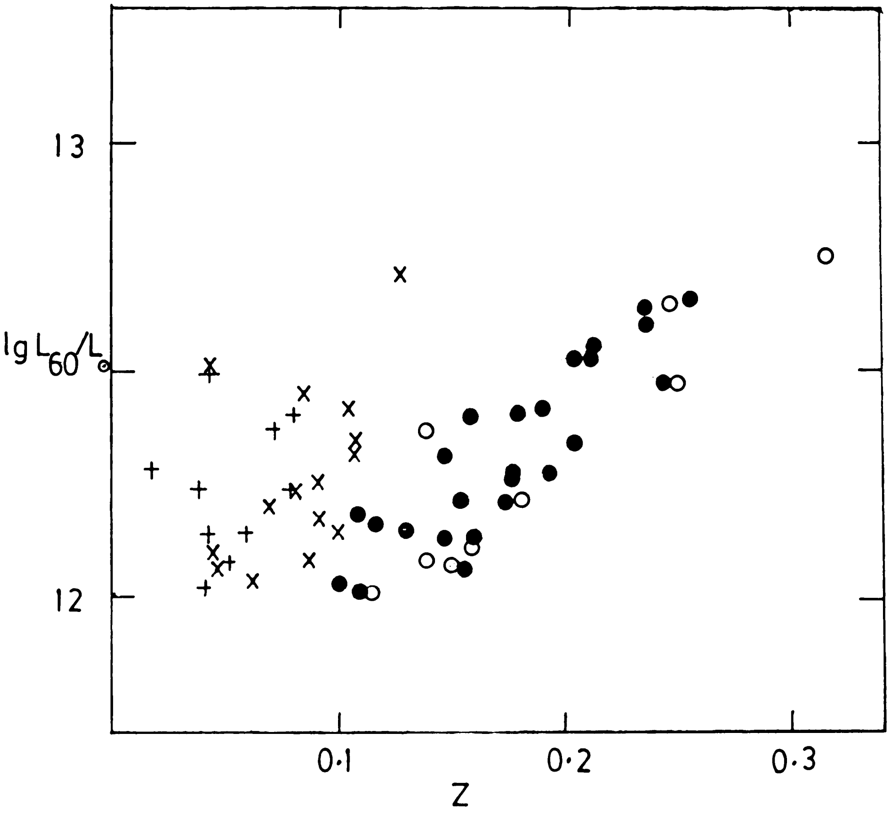

Fig 7: log L_{60}/L_{0} versus redshift for galaxies with $L_{60} > 10^{12}$ L_{0}. Crosses: data from Sanders et al(1988), x's: data from Melnick and Mirabel (1990), filled circles: interacting, peculiar or merging galaxies from Leech et al (1990), open circles: galaxies which do not show evidence of interaction from Leech et al (1990).

Telescope and found that all are interecting or merging. Leech et al (1990) have now imaged 40 IRAS galaxies with $L_{60} > 10^{12}$ L_o using the INT, and found that 72 % are interacting, merging or peculiar, 11 % have companions, but no evidence for strong interaction, and 17% show no evidence for interaction.

If we now combine the samples of Sanders et al (1988), Lawrence et al (1989), Melnick and Mirabel (1990) and Leech et al (1990) we find the following interesting results:

log $\{L_{60}/L_o\}$ (H_o=50, Ω_o=1)	number	% interacting/merging
< 11.0	101	17%
11.0 - 11.5	17	47%
11.5 - 12.0	24	58%
12.0 - 12.25	30	83%
12.25-12.5	20	90%
12.5 - 12.75	10	90%

The percentage of interacting or merging galaxies increases steadily with increasing luminosity, reaching the very high figure of 90% for the very highest luminosities. The data are summarized in Fig 7, a plot of log L_{60} against redshift. The disagreements between the different groups are now within the statistical uncertainties.

Some recent studies of individual interacting or merging systems are those by Neff et al (1989) of NGC 1614, by Joy et al (1989) of NGC 3690, by Nakagawa et al (1989) of NGC 3690, by Carico et al (1990) of 9 galaxies, by Thronson et al (1990) of NGC 6240, by van Driel et al (1990) of 3 galaxies, by Lutz(1990) of 4 galaxies, and by Forbes (1990) of NGC 1052.

There still appears to remain a significant disagreement about the proportion of ultraluminous infrared galaxies that are Seyferts or liners. Sanders et al (1988) found that 9/10 ultraluminous IRAS galaxies had line ratios characteristic of Seyferts or liners in their nucleus (revised to 8/10 in the review by Sanders 1990), whereas Leech et al (1989) found that only 2/13 ultraluminous galaxies were Seyferts or liners. This merits further study.

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Left table: Fran Verter, A. Poglitsch and. A. Krabbe. Right table: Santiago Garcia-Burillo, Pierre Martin and Pierre Cox (both in the retrograde sense).