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Enhanced star formation – the importance of bars in spiral galaxies

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Summary. *IRAS* results demonstrate that, amongst intrinsically luminous spiral galaxies, more than one third of the barred systems have an excess of flux at 25 μm. The mean total infrared luminosity of these systems ($4.3\times10^{10}\,L_{\odot}$) is more than twice that of unbarred galaxies ($1.7\times10^{10}\,L_{\odot}$), few or none of which exhibit a 25 μm excess. We show that these properties are probably attributable to vigorous star formation in a 'circumnuclear' ring located near an inner resonance where material from a bar-driven inflow accumulates, and infer also that an active nucleus does not dominate this phenomenon.

1 Introduction

Two characteristic features of barred spiral galaxies of early to intermediate type are the dust lanes which trace the hydrodynamic shocks in the bar, and the associated rings of H II regions around the nucleus. Observations of H I by Sancisi, Allen & Sullivan (1979), and optical spectroscopy by Pence & Blackman (1984), for example, suggest that in such structures there is a bar-driven inflow of material. Theoretical models (e.g. Schwarz 1984; Combes & Gerin 1985) suggest that these 'circumnuclear' rings are situated near one of the inner resonances and that this is where material swept inwards would accumulate. At least two of these rings (in NGC 1097 and 3310) are unambiguously the location of enhanced star formation (Telesco & Gatley 1981, 1984).

As the radiation from star-forming regions is absorbed by dust and re-radiated in the mid- to far-infrared, we have used the unbiased all-sky survey provided by the *IRAS Point Source Catalog* (see the Explanatory Supplement, edited by Beichman *et al.* 1984) to study this process in spiral galaxies from the *Revised Shapley-Ames Catalog* (Sandage & Tammann 1981, 'RSA').

2 The sample of galaxies

The *IRAS* fluxes of star-forming regions rise steeply between band 1 and band 2 (12 and 25 μm), a consequence of the presence of a large component of 'warm' dust at temperatures around 100 K

(Adams & Shu 1985). To investigate their incidence in galaxies, we have constructed a two-colour diagram using the ratio of the fluxes in bands 1 and 2 and that between bands 4 (100 μm) and 2. This allows us to distinguish between this 'warm' component and the ubiquitous 'cool' dust (Cox, Krügel & Mezger 1986). Our sample comprises all objects in the RSA with morphological classifications in the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs & Corwin 1976, 'RC2') between SO/a and Scd (inclusive) which have been detected by *IRAS* in all four bands. We have excluded those which are resolved by *IRAS* at 100 μm (as indicated by the point-source correlation coefficient) and those with serious cirrus contamination (cirrus 2 flag$\geq$4). We have also omitted those galaxies listed as Seyferts of types 1 or 2 or as LINERs by Véron-Cetty & Véron (1985, hereafter VCV). One hundred and eighty-six galaxies have been included.

3 Analysis of the *IRAS* results for the sample galaxies

Fig. 1(a), (b) and (c) show the distributions in the two-colour diagram for galaxies in our sample of type SB, SAB and SA, respectively. There is a dramatic difference between these distributions. A large fraction of the SB and many of the SAB galaxies have greatly enhanced 25 μm fluxes relative to their 12 μm and 100 μm fluxes. These galaxies include NGC 1097 and 3310, the positions of which are shown. We interpret this excess flux at 25 μm as arising in regions of active star formation and infer that high levels of this activity, sufficient to dominate the infrared colours of galaxies, *occur almost exclusively in the barred systems*.

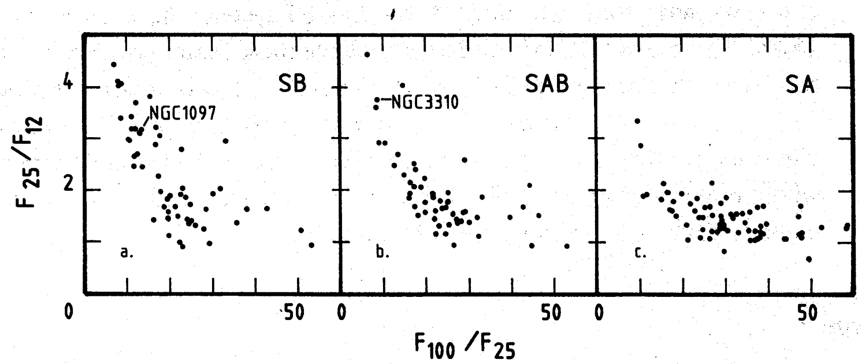

Figure 1. The distributions of SB, SAB and SA galaxies in the *IRAS* two-colour diagram, $f_\nu(25\,\mu\text{m})/f_\nu(12\,\mu\text{m})$ against $f_\nu(100\,\mu\text{m})/f_\nu(25\,\mu\text{m})$, are shown in (a), (b) and (c) respectively. The classification is from the RC2 and comprises a sub-set of all galaxies in the RSA detected by *IRAS* in all four bands. The two 'starburst' galaxies NGC 1097 and 3310 are marked.

Fig. 1 suggests that the galaxies with 'excess' star-forming activity are conveniently distinguished by values of the 2/1 ratio >2.2 because '*normal' galaxies evidently have flat spectra between 12 and 25 μm*. We have adopted the prefixes h and l for galaxies falling above and below this division.

Fig. 2 compares the distributions of (a) distance (corrected for group or cluster membership), (b) uncorrected total *B* magnitude, and (c) the distance-independent ratio [total far-infrared luminosity/total *B* luminosity] for *IRAS*-detected RSA spirals in our range of Hubble types with and without band 1 detections; the former comprise our sample in Fig. 1. The far-infrared flux parameter (FIR) is a linear combination of the 60 μm and 100 μm flux densities (Lonsdale *et al.* 1985). The detected galaxies are closer and optically brighter than the undetected objects but the difference is small. Conversely Fig. 2(c) shows that the sample in Fig. 1 is much more luminous in the far-infrared, relative to the blue, than the undetected systems.

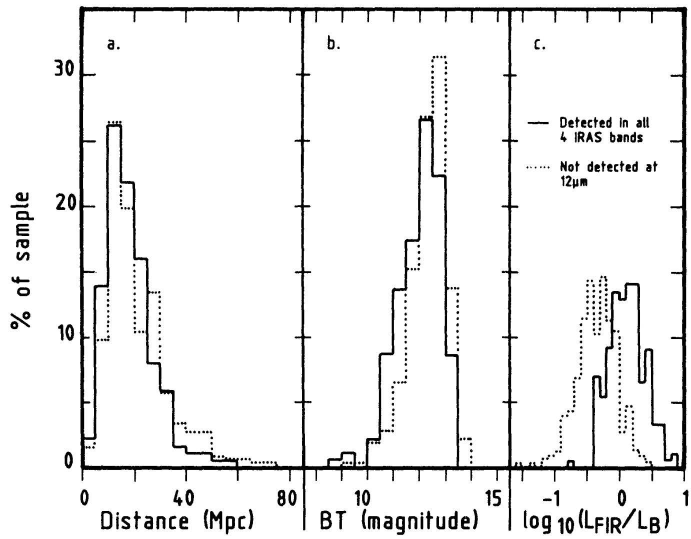

Figure 2. Comparisons between the samples of RSA galaxies detected in all *IRAS* bands (i.e. those in Fig. 1) (solid lines) and galaxies not detected at 12 μm (broken lines) showing the distributions of (a) distance, (b) uncorrected total *B* magnitude and (c) total FIR luminosity/*B* luminosity for each group.

The ratio of SA:SAB:SB galaxies in our sample (74:55:53) is similar to those not detected at 12 μm (98:103:110) and so our selection does not favour a particular morphology. As, surprisingly, bars are not over-represented in our intrinsically infrared-luminous sample, this suggests that the phenomena shown in Fig. 1 may only be important at high infrared luminosities, as remarked by Devereux, Becklin & Scoville (1986).

The hSB galaxies in Fig. 1 have a mean total infrared luminosity $\langle \mathrm{LIR} \rangle = 4.3 \times 10^{10} L_\odot$ ($H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), markedly brighter than the lSB systems with $\langle \mathrm{LIR} \rangle = 2.8 \times 10^{10} L_\odot$. These are, in turn, more luminous than the SA galaxies with $\langle \mathrm{LIR} \rangle = 1.7 \times 10^{10} L_\odot$.

4 Discussion

To support our assertion that the galaxies exhibiting 25-μm excesses have greatly enhanced rates of star formation, we have constructed simple models using the averaged observed *IRAS* fluxes of a group of luminous, unresolved H II regions in a field in Cygnus. Addition of about 10^5 such objects to a model galaxy having the mean colours and total infrared luminosities of the SA systems in Fig. 1 reproduces quite accurately the *IRAS* colours and luminosities of a typical 'starburst' system such as NGC 1097. Only the 12-μm emission is underestimated. Wynn-Williams & Becklin (1985) showed that galactic H II regions are significantly redder than the integrated *IRAS* colours of extragalactic star-forming complexes and attributed this excess emission at 12 μm to fluorescent small grains. Our models so far omit the extended 12 μm emission seen by *IRAS* across the whole Cygnus complex (described in a future paper). In many respects these models resemble those of Rowan-Robinson & Crawford (1986) who also find enhanced star formation in barred galaxies.

Since star formation occurs in the discs of barred and unbarred galaxies alike, the discs are unlikely to be the source of the 25 μm excess amongst the 'h' galaxies. Hummel (1981) finds that at 21 cm unresolved (<20 arcsec) centrally concentrated continuum emission sources are significantly more luminous in barred than in unbarred galaxies, whereas the radio emission from the discs of barred and unbarred systems is indistinguishable. Hummel suggests that this continuum emission may trace the density of the ISM or the local star-formation rate. Helou, Soifer & Rowan-Robinson (1985) also find a tight correlation between the radio continuum and the *IRAS* far-infrared flux. We have undertaken observations similar to those of Hummel which increase the overlap between the radio and infrared samples (Puxley *et al.*, in preparation). Initial results show that *all* the hSB and hSAB galaxies were detected at 21 cm and exhibit unresolved central sources, while only 20 per cent of the 'l' galaxies do so. These results strongly suggest that the star-forming regions which dominate the infrared colours are located within 20 arcsec of the galactic nuclei.

There remains the possibility that we are seeing phenomena causally associated with a compact nuclear source. We excluded from our initial sample all galaxies classified as Seyferts or LINER's in VCV. Fig. 3 shows the two-colour diagram for these galaxies, which exhibit a remarkably similar distribution to that of the spirals, even to the presence of the 'split' at 2/1 ~2. However, the accuracy with which the colours and luminosities of the 'h' galaxies are reproduced by the addition of H II regions to an 'l' system suggests that the nucleus does not have a significant effect on star formation in our sample.

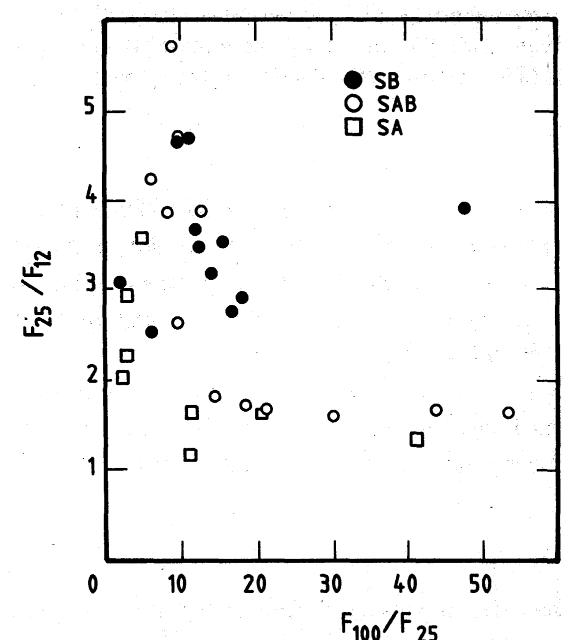

Figure 3. As for Fig. 1 but showing the galaxies excluded from that diagram because of the presence of Seyfert 1 or 2 or LINER features in their spectra.

5 Conclusions

In our sample, galaxies with *IRAS* flux ratios 2/1>2.2 are exclusively barred (with two exceptions) and have enhanced star formation which is probably concentrated within the central 20 arcsec, but not caused by nuclear activity. These hSB and hSAB systems have higher 60 μm and 100 μm luminosities than the 'l' galaxies of all families, but it is possible to account for all the extra luminosity in the 'h' systems by adding the 'average' spectrum and luminosity of $\sim 10^5$ galactic H II regions to an 'l' SA galaxy.

We conclude that, in the absence of violent interaction or an active nucleus, the circumnuclear rings in barred galaxies are the only locations in spirals earlier than Scd where vigorous star-forming activity occurs (see also Elmegreen 1986).

We speculate that NGC 3885 and 6810, the only two non-barred 'h' galaxies, may in fact be barred. On UK Schmidt IIIa-J plates NGC 6810, although dustier, resembles the 'starburst' SAB system NGC 253 and quite probably contains an obscured bar. NGC 3885 has strong dust lanes characteristic of barred systems: Corwin (private communication) informs us that some have classified this galaxy SAB.

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