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ON THE ORIGIN OF THE 40-120 MICRON EMISSION OF GALAXY DISKS: A COMPARISON WITH H-ALPHA FLUXES

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Abstract

A comparison of 40-120 micron IRAS fluxes with published H-alpha and UBV photometry shows that the far infrared emission of galaxy disks consists of at least two components: a warm one associated with OB stars in HII-regions and young star-forming complexes, and a cooler one from dust in the diffuse, neutral interstellar medium, heated by the more general interstellar radiation field of the old disk population (a 'cirrus'-like component). Most spiral galaxies are dominated by emission from the cooler component in this model. A significant fraction of the power for the cool component must originate with non-ionizing stars. For a normal spiral disk there is a substantial uncertainty in a star formation rate derived using either the H-alpha or the far infrared luminosity.

1. INTRODUCTION

There is now a general consensus that the far infrared flux of the Galactic disk originates in part in the diffuse neutral and ionized media, heated by the general interstellar radiation field in these regions (eg. Cox and Mezger 1987). In this paper, which summarises the results of Lonsdale Persson and Helou (1987), we explore the extent to which the IRAS-measured 40-120 micron fluxes of a sample of normal disk galaxies can be attributed to the different regimes (young HII-region/GMC complexes, the diffuse neutral medium and low density HII-regions) and stellar populations (OB stars, A and later stars) which contribute to the Galactic far infrared (1-1000 micron) emission, by comparison of the 40-120 micron flux with the H-alpha flux. If the emission of galaxy disks in the IRAS bands is dominated by emission from young OB stars (either optically visible or GMC-embedded), then the IRAS fluxes might be expected to be highly correlated with H-alpha fluxes. Conversely, a poor correlation of far infrared with H-alpha flux might imply large dispersion in H-alpha extinction, far infrared emission from a mixture of HII-regions of varying density and dustiness, or a substantial contribution to the far infrared emission from older and less massive stars.

The H-alpha fluxes are taken from Kennicutt and Kent (1983), who made large aperture H-alpha+[NII] observations of over 100 disk galaxies. Our restricted sample of 54 galaxies represents all those in Kennicutt and Kent's list with high quality H-alpha, 60 micron and 100 micron fluxes, and with 60 micron flux density

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greater than 2 Jy. Also, galaxies for which a significant part (>20%, as defined by Kennicutt and Kent) of the H-alpha emission originates in the nucleus, or which are known to possess Seyfert or starburst nuclei, were excluded since the primary interest here is disk emission. The measured H-alpha+[NII] fluxes were corrected for extinction and [NII] emission as recommended by Kennicutt (1983).

2. RESULTS

In Figure 1 we plot the 40-120 micron flux of the sample against the H-alpha flux and the blue flux. This far infrared flux is derived from the sum of the fluxes in the 60 and 100 micron bands (Cataloged Galaxies in the IRAS Survey, 1985, Appendix B). We have chosen not to extrapolate to 'total' (1-1000 micron) far infrared/submillimeter fluxes for the general analysis because of the uncertainties in the dust grain emissivity law and temperature distribution.

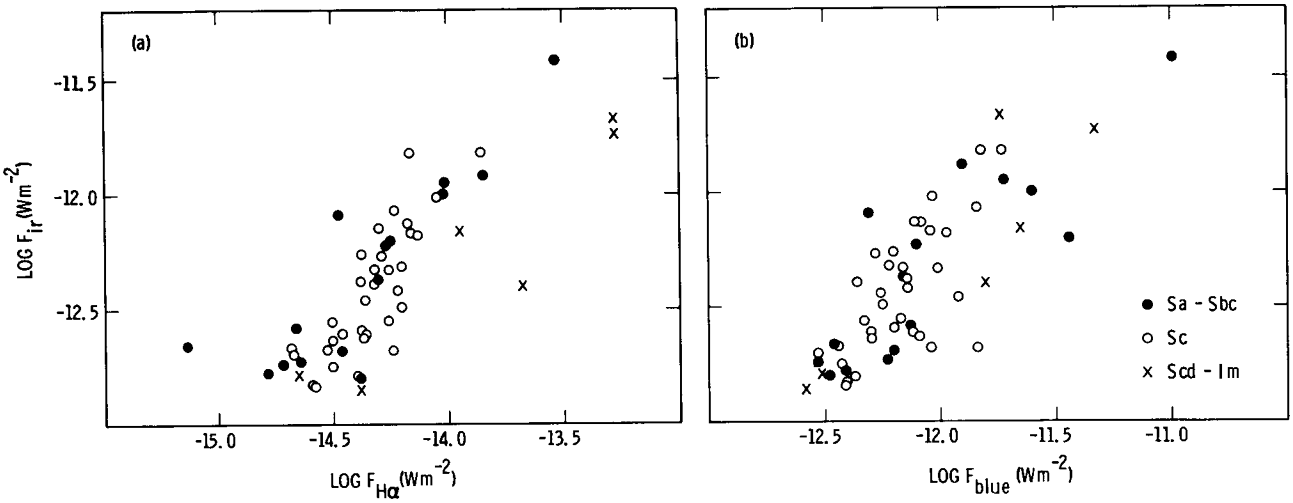
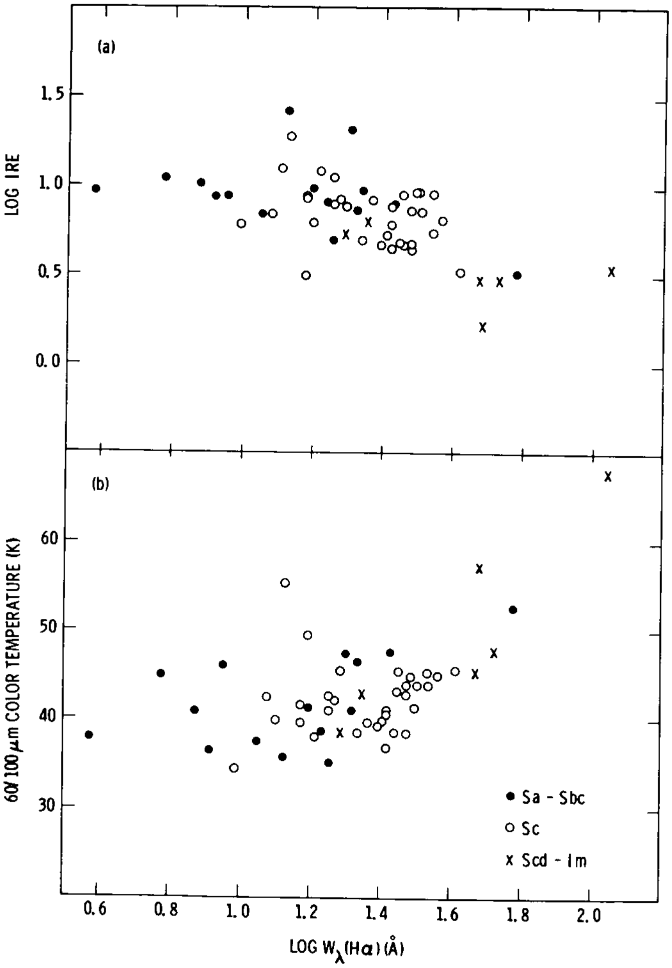


Figure 1. Correlation between far infrared and (a) H-alpha and (b) blue fluxes (derived from the extinction and inclination corrected blue magnitudes in de Vaucouleurs, de Vaucouleurs and Corwin 1976) The 54 galaxies are binned by revised Hubble type (Sandage and Tammann 1981).

The correlation between the far infrared and H-alpha flux seen in Fig 1a is quite good, with a slope consistent with unity and a Spearman's rank-order correlation coefficient r=0.81. Fig. 1b, however, shows just as good a correlation (r=0.79) between the far infrared flux and the flux within the blue filter. Good correlations still exist when both axes in these figures are normalised by the square of the angular diameter or when luminosities are plotted instead of fluxes (not shown), thus the correlations are not due to underlying correlations with distance or mass.

To investigate further the contribution to the far infrared flux by the stellar population responsible for the blue light, we derive the infrared excess, IRE, defined as the ratio of the infrared luminosity (here taken as the 40-120 micron luminosity) to the Lyman alpha luminosity (derived from the H-alpha luminosity). In Figures 2 and 3 we show the relationships of IRE and of the 60/100 micron color temperature to the equivalent width of H-alpha and the (B-V) color, respectively. IRE is proportional to the ratio of the axes of Fig. 1a, so since the slope of the relationship in that figure is consistent with unity, IRE is a measure of the residuals from the mean relation.



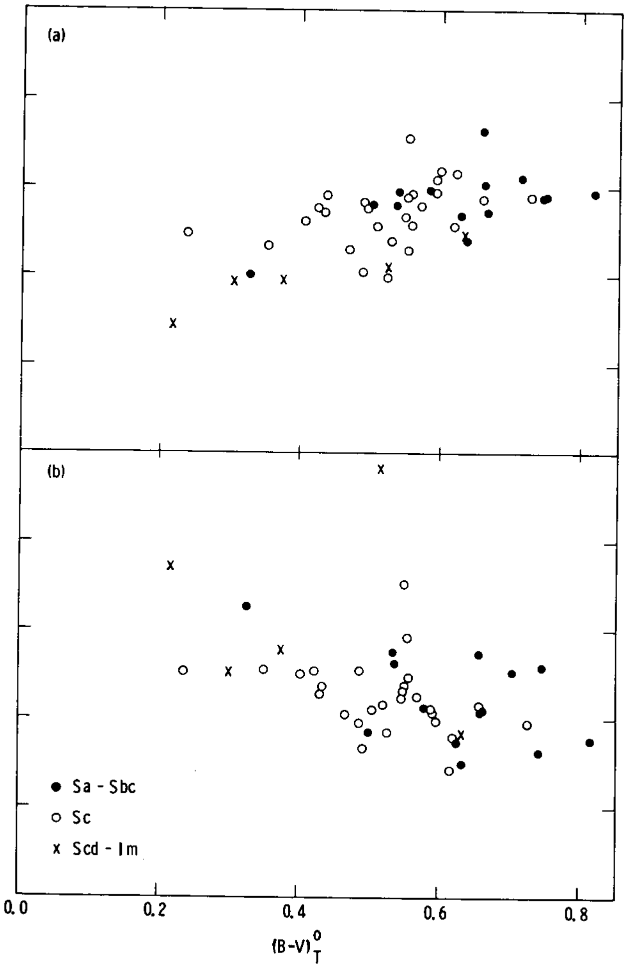


Figure 2. Relationships between the equivalent width of H-alpha and (a) the infrared excess (the 40-120 micron flux in units of the Lyman alpha flux) and (b) the 60/100 micron color temperature.

Figure 3. Relationships between (B-V) color (from de Vaucouleurs, de Vaucouleurs and Corwin 1976) and (a) the infrared excess and (b) 60/100 micron color temperature.

There is a tendency for IRE to decrease, and the color temperature to increase with the H-alpha equivalent width, which is a measure of the current relative star formation rate (Kennicutt 1983). Also, galaxies which are red in (B-V) tend to be cooler in the far infrared, and to have larger IRE. Similar relationships are seen with (U-B). It is also apparent that IRE decreases towards later morphological type, but no general gradient in color temperature can be distinguished with type, apart from the fact that very late types tend to be relatively warm, as also found by others.

3. INTERPRETATION AND MODELLING

On the basis of Fig. 1 we conclude that the 40-120 micron flux of galaxies may be powered in part by the stellar populations responsible for the blue flux, in addition to the HII-regions. The blue flux is dominated by old disk stars of 1-2 solar mass characteristic mass (Searle, Sargent and Bagnuolo 1973; Lequeux 1986; Renzini and Buzzoni 1986), which implies significant input to the far infrared flux from non-ionizing stars.

Figures 2 and 3 indicate that the coolest galaxies, which have 60/100 micron ratios similar to that of Galactic cirrus emission (Gautier 1986), tend to have high IRE, low H-alpha equivalent width and red UBV colors, while warm galaxies have 60/100 micron values which are more typical of compact HII-regions (Chini et al. 1986a,b). For these objects, IRE tends to be low, the equivalent width high and the UBV colors blue. Thus high IRE is apparently anti-correlated with optical indicators of a high star formation rate, and with dust temperature.

The simplest ways to explain this result are (i) that the far infrared flux is powered predominantly by OB stars and the trends seen in Figures 2 and 3 are due to a large dispersion in dust optical depth; (ii) that there are at least two far infrared flux components contributing to the IRAS-observed emission: a warm, low-IRE one originating with the OB star population and a cooler high-IRE one powered by the general interstellar radiation field and not strongly related to the HII-regions; and (iii) that the variations in observed IRE are driven by a changing IMF, such that the HII-regions in the high equivalent width galaxies are powered by hotter stars, resulting in higher dust temperatures and lower IREs (Panagia 1974).

We favor the second possibility described above as the most likely scenario for spiral disks with steady state star formation, which make up the bulk of our sample. A strong objection to the first model is that if the decrease in B-V in Fig. 3a were to be attributed to reddening, a visual extinction of more than two magnitudes would be required. This is much larger than typical galaxian internal extinctions. Also, there is a rough separation by Hubble-type in Fig. 3 in a sense consistent with dominance of the

B-V color by stellar populations rather by reddening. An objection to effect (iii) is that though it is likely to be operating to some extent in the high star formation rate late type galaxies such as NGC 4449 and NGC 1569, it is somewhat artificial for large disks undergoing steady state star formation.

Besides these objections raised to the other models, we favor the second interpretation because (a) there exist normal HI-rich spirals with little or no detectable H-alpha flux, which are not particularly dusty yet have normal IRAS-measured far infrared fluxes (Bothun 1986); (b) it is similar in concept to the current understanding of the situation in our own Galaxy (eg. Cox and Mezger, 1987); and (c) galaxies are known to possess substantial flux at wavelengths greater than the IRAS limit (Telesco and Harper 1980; Smith 1982; Rickard and Harvey 1984; Chini *et al.* 1984a,b) which would be identified with the cooler of the two components we propose.

To estimate the approximate contribution of the two components to the total far infrared flux we have constructed a simple two component model: a 'warm' component to be associated with the young OB star population, and a 'cool' one associated with interstellar radiation field heating of diffuse neutral material. All the H-alpha flux is associated with the warm component. Each model is defined by the 60/100 micron flux density ratio of the warm and cool component, selected to lie at or beyond the extrema of the observed distribution of this ratio and to be consistent with colors of HII complexes (Chini *et al.* 1986a,b) and of cirrus (Gautier 1986), respectively. Three values of each temperature were considered. For each galaxy and each model the combination of the two components was found that matches the observed far infrared flux and 60/100 micron ratio.

Models with warm and cool model component color temperatures of approximately 50 to 80 and 20 to 26 K, respectively, are able to fit all the sample galaxies. For these models, the contribution to the 'total' far infrared luminosity (an extrapolation of the 40-120 micron luminosity over a Planck function assuming that dust emissivity falls as the square of the wavelength) of the galaxy disks from the two components is roughly equal, with somewhat more arising in the cooler component. The 'total' IRE (derived from the 'total' far infrared luminosity) of the warm component lies in the range 2-10 for the bulk of the sample.

4. DISCUSSION

We have concluded from our simple model that in most disk galaxies a cool component, interpreted as 'cirrus' emission (dust in the diffuse neutral interstellar medium heated by the interstellar radiation field) is responsible for >50% of the 'total' far infrared flux, and that the intrinsic 'total' IRE of the remaining warm OB star-powered emission lies in the range 2-10.

We have checked that there is sufficient power in the interstellar radiation field to account for the observed infrared luminosity of the cool model component, and a large enough optical depth in the diffuse medium to absorb this energy for re-radiation in the far infrared, by comparison with the solar neighborhood cirrus models of Draine and Anderson (1985). We find that the ratio of the 100 micron flux to the HI line flux (Huchtmeier et al. 1983) is quite comparable to that predicted by the models of Draine and Anderson (1985) for most of our sample.

A good test of the existence of the cool component cirrus emission is long wavelength photometry. Only two of our sample galaxies have been measured at wavelengths longer than the IRAS limit. For these, NGC 4449 (Thronson et al. 1986) and NGC 4736 (Chini et al. 1984b), the long wavelength photometry is in better agreement with our two component model than with a single component interpretation of the far infrared data.

The infrared excess of our model warm component may be compared with predictions for model HII-regions, which vary from values as low as about 3 for low density HII-regions (Caux et al. 1984; Mezger, Mathis and Panagia 1982) to >9 (Hauser et al. 1984) depending on assumptions about the IMF, the optical depth of the gas and dust to the ionizing and non-ionizing continuum and the lines, and the gas density. Larger values can occur if very young dust-embedded stars dominate the emission, or if non-ionizing (late B and early A) stars belonging to the OB associations contribute a significant heating flux.

About 10% of the galaxies have an IRE of 2-3 for the warm model component, including half of the Sd-Im galaxies. Hence for these galaxies there is little evidence that the integrated H-alpha emission is seriously affected by extinction, or that GMC-embedded stars or very compact HII-regions are a significant fraction of the total OB star population (see also Hunter et al. 1986 and Kunth and Sevre 1986). Thus the far infrared flux of these galaxies comes primarily from the vicinity of the low density HII-regions, and the H-alpha-derived star formation rates are probably reasonably accurate.

For the remainder of the sample, which have relatively large IREs, it is not possible to rule out (a) a significant H-alpha extinction, (b) a significant trapping of the ionizing continuum by dust, or (c) a contribution to the warm component far infrared flux from either non-ionizing stars or from very young dust-embedded OB stars. Thus it is possible for these galaxies that star formation rates derived from H-alpha fluxes are severely underestimated. In view of the ambiguities associated with the interpretation of the warm component far infrared luminosity of these galaxies, it is not possible to derive reliable star formation rates from the IRAS far infrared data either.

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DISCUSSION

MEZGER: This is more a comment than a question. In all cases in which we have extended the spectra of IRAS galaxies by observations at 350 and 1300 microns we find that (i) the 100-1000 micron luminosity is comparable to the 25-100 micron luminosity, and (ii) cold dust emission contributes a non-negligible fraction to the 100 micron flux density. This certainly complicates a spectral analysis based on IRAS data alone, and makes the interpretation of the 60/100 micron ratio in terms of a color temperature somewhat questionable.

REPLY: I agree. In fact the cold dust contribution to the 100 micron flux is just the point that we are making. Our approach is based on the fact that it is IRAS data that we now have available for thousands of galaxies, and we must understand clearly the limits to which we can use it. After making the model decomposition based on 60/100 micron color temperature, we made a correction to both the warm and cool component fluxes for flux beyond the IRAS limits. These corrections are about a factor of 1.5 - 2, similar to what you find. Also, we find a similar fraction of the total (1-1000 micron) far infrared flux to be coming from the cool component as you do.

MEZGER: Yes, we are in general agreement.