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A SIMPLE TWO-COMPONENT MODEL FOR THE FAR-INFRARED EMISSION FROM GALAXIES

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ABSTRACT. We have constructed a simple model to calculate the far-infrared emission of galaxies made up of a disk component containing cool dust heated by the general interstellar radiation field and of a molecular cloud component containing warm dust heated by recently formed massive stars. This model is fitted to the optical and far-infrared data of 120 Shapley-Ames galaxies and of 20 optically studied mini-survey galaxies, resulting in the determination of blue face-on extinctions and of the total luminosities of recently born massive stars and of disk stars. The ratio of these two luminosities is a more reliable star formation activity index than the previously often used ratio L_{IR}/L_B. The results show that infrared selected galaxies are on the average almost three times more dusty than optically selected ones. Only about 10% of the mini-survey galaxies exhibits strongly enhanced star formation.

1. INTRODUCTION

A large fraction of the energy emitted by recently formed massive stars is reradiated in the far-infrared by dust grains in molecular clouds - the dominant site of massive star formation in a galaxy. This makes the infrared by far the most suitable wavelength range to study the energetics of star formation and to derive global star formation rates in galaxies.

However there are additional sources of infrared radiation in a galaxy that complicate the picture. Dust particles in the general interstellar medium, predominantly heated by much older field stars, also contribute to the total infrared emission. This dust is probably cooler than the dust in molecular clouds (cf. Mezger et al. 1982, de Jong et al. 1984). Furthermore, hot dust has been shown to be present in the nuclei of active galaxies (de Grijp et al. 1985).

If infrared observations of galaxies with high spatial resolution would be available the different infrared components could be separated directly. However, because of the large detector sizes (typically several arcminutes, cf. Neugebauer et al. 1984) the IRAS data, on which our study will be based, provide only total energy information.

Thus to study star formation in galaxies the observed infrared emission has to be decomposed into several components. In this paper we present some preliminary results of fitting simple two-component models to the IRAS 60 and 100 μm fluxes of about 140 galaxies.

2. THE MODEL

The purpose of our model calculation is to fit the observed 60 and 100 µm fluxes and the B_T magnitude of a galaxy. In addition to these three observables the model also makes use of the observed galaxy inclination (or equivalently the axial ratio b/a).

First we fit two infrared components to the observed infrared spectral energy distribution. To do so we assign a dust temperature T_w to the warm dust in molecular clouds and T_c to the cool dust in the general interstellar medium (the disk component). We further assume that the dust emissivity is proportional to λ^{-1}. This fit results in 60 and 100 µm fluxes for each component, that add up to the observed fluxes. We then calculate the total luminosity of each component, L_w and L_c, by integrating over all wavelengths.

Next we calculate the total luminosity of recently formed massive stars, L_2, by assuming that half of the luminosity of these stars is completely converted to infrared radiation inside molecular clouds, so that $L_2 = 2L_w$. The other half is emitted by stars that have moved away from the molecular clouds in which they were born within their lifetime. The 50% estimate above has been derived for stars born with a Salpeter initial mass function (IMF) and a cloud residence time of 3 10^6 yrs (cf. Garmany et al. 1982), i.e. for stars moving with velocities of 10 km s^{-1} in clouds with sizes of order 60 pc. The fact that we do observe OB stars is convincing evidence that an appreciable fraction of them indeed escapes from clouds within their lifetimes.

To calculate the luminosity L_1 of disk stars, that are largely responsible for the blue luminosity of a galaxy and for the heating of the cool interstellar dust, we assume a surface black-body temperature for these stars of T_1 = 7000 K. Anticipating the result that in a typical spiral galaxy $L_2/L_1 \simeq 0.5$ (see section 3) and taking T_2 = 30,000 K (see below) the mean colour temperature of the interstellar radiation field is found to be 12,000 K, close to the canonical value of 10,000 K.

However, OB stars outside molecular clouds also contribute to the heating of the interstellar dust and to the observed blue light. The effective temperature of these stars is about 30,000 K, another result of the calculation of the fraction of the luminosity emitted outside clouds by stars born with a Salpeter IMF inside molecular clouds. Taking account of the fact that the interstellar absorption roughly scales with $1/\lambda$ so that the effective optical thickness of the disk for 7000 K and 30,000 K radiation is different, we iteratively solve for the dust optical thickness at λ4400, τ_B, of the galactic disk (equivalent to the face-on extinction) and L_1. To fit the observed blue magnitude we take into account that the blue light is attenuated by optical thickness $(a/b)\tau_B$. The face-on extinction is then found from the relation $A_B^0 = 1.086\ \tau_B$.

Our model thus results in the determination of the face-on blue extinction A_B^0 of a galaxy and of the luminosities L_1 and L_2. The quantity L_2/L_1 is a much better measure of the ratio of present-to-past star formation rates than the often used quantity L_{IR}/L_B (de Jong et al. 1984, Soifer et al. 1984).

3. RESULTS AND DISCUSSION

We have fitted our simple two-component model to infrared and optical data of 120 galaxies in the Revised Shapley-Ames Catalog of Bright Galaxies (Sandage and Tammann 1981) and to the data of 20 mini-survey galaxies (Soifer et al. 1984) for which morphological classifications, detailed optical and infrared photometry and optical spectra have recently been presented by Moorwood et al. (1986). Infrared flux densities of these galaxies were taken from the IRAS Point Source Catalog (JISWG 1985), supplemented by flux densities from the IRAS Small Scale Structure Catalog (JISWG 1986), if listed. Optical blue magnitudes of both the RSA galaxies and of the mini-survey galaxies were corrected for extinction in our own galaxy according to the prescriptions given by Sandage and Tammann (1981).

For our model calculations we took T_w = 60 K and T_c = 16 K. These are not arbitrary choices but were selected as follows. T_w was chosen to be somewhat larger than the largest dust temperature as derived from the observed S_{100}/S_{60} flux density ratios. T_c was chosen such that the average face-on extinction derived for the RSA galaxies agreed with optically determined values (see fig.1 and discussion below). The low temperature of the cool component implies that a substantial fraction of the total infrared luminosity of galaxies (more than 50% in most cases) is emitted at wavelengths longward of 100 μm.

We note that our adopted values of T_w and T_c are remarkably close to the ones recently derived by Chini et al. (1986) by combining sub-millimeter observations with IRAS data for about 20 bright galaxies. This agreement may be somewhat fortuitous because Chini et al. assumed a λ^{-2} dust emissivity law.

We have verified that the results are rather insensitive to changes in the adopted parameters. The largest effect is observed for T_c, understandably because L_c changes significantly if T_c changes by only a few degrees. We emphasize that the value adopted for T_c is found by fitting optical extinction measurements of galaxies and is thus rather well-determined.

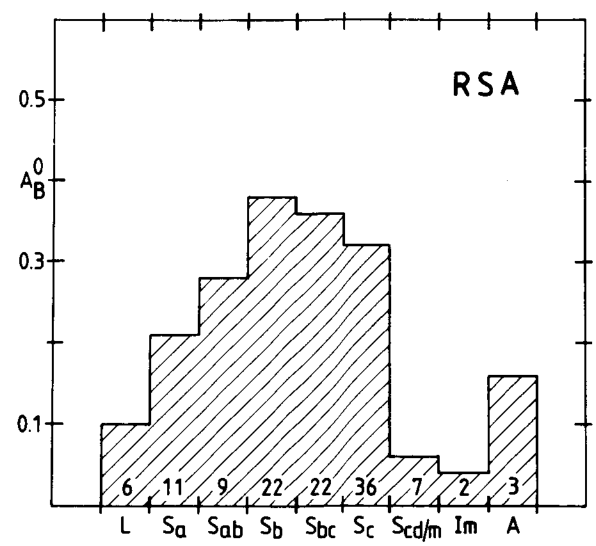

Figure 1. Mean values of the face-on blue extinction A_B^0 as a function of morphological type. The numbers of galaxies on which this mean value is based, are listed.

The distribution of average face-on blue extinctions as a function of morphological type for the RSA galaxies is shown in fig.1. Formal uncertainties in the averages are typically of order 10% - 20%. As noted above the temperature of the cool dust has been fixed by requiring that the weighted mean of A_B^0 over all spirals equals that calculated using the prescriptions of Sandage and Tammann (1981). The somewhat higher values for S_a and S_{ab} galaxies quoted by Sandage and Tammann may be due to the exclusion of dust-poor galaxies in their determination of A_B^0 for the earliest morphological types.

The variation of A_B^0 with morphological type is quite interesting and seems intuitively rather plausible. A_B^0 is small for early-type galaxies because they contain relatively small amounts of interstellar matter and thus also of dust. Proceeding to later morphological types the mass fraction of interstellar matter increases and so does the face-on extinction. For the latest morphological types we deal with galaxies in which evolution has been so slow or in which star formation has started so late that their metallicity is still relatively low, showing up here as a low face-on extinction.

In fig.2 we compare values of A_B^0 and of the recent star formation activity index $\log(L_2/L_1)$ for an optically complete sub-set of about 50 bright RSA spirals ($B_T < 12.5$, $V_R > 500$ km s^{-1}) and for the sub-set of the infrared-complete mini-survey galaxies studied by Moorwood et al. (1986). The most important conclusion to be drawn from this comparison is that the mini-survey galaxies are on the average almost three times more dusty while the present star formation activity is only about twice as large as in the RSA spirals. The

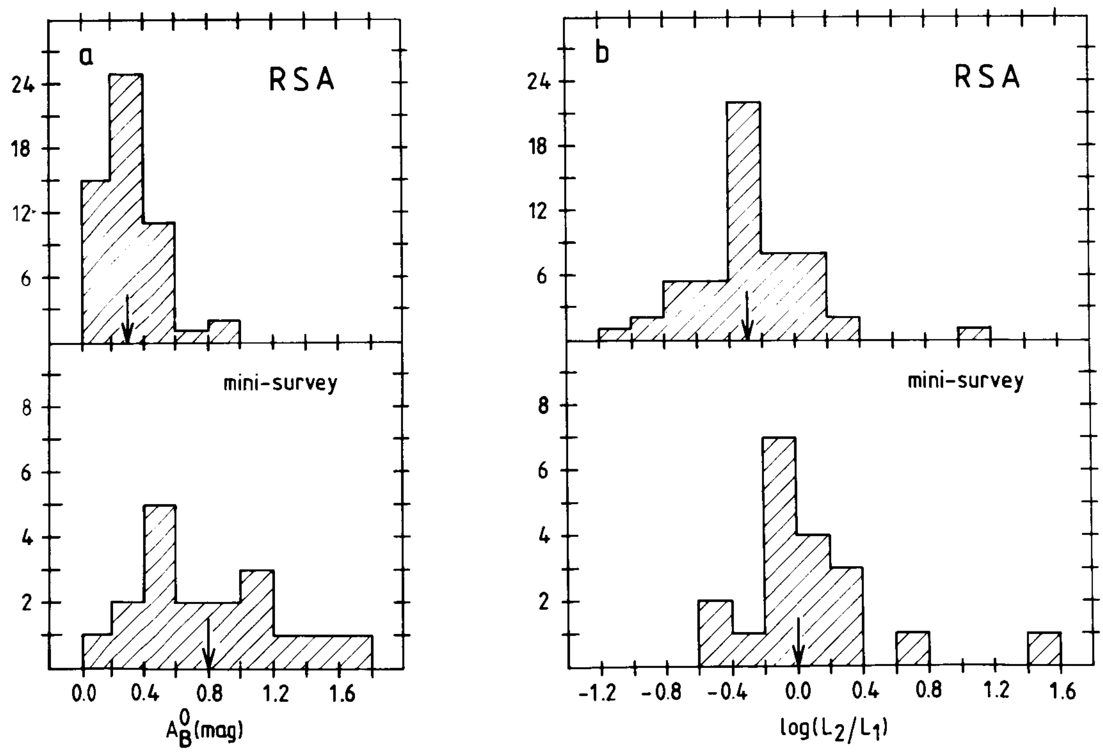

Figure 2. The distribution of: (a) blue face-on extinction A_B^0, and (b) star formation activity index $\log(L_2/L_1)$ for bright optically selected RSA spirals and infrared selected mini-survey galaxies.

latter may be fully explained by realizing that galaxies with higher present star formation rates are expected to be overrepresented in an infrared complete sample of galaxies. Thus we conclude that infrared selected samples of galaxies are apparently dominated by dusty galaxies.

This possibility was already briefly discussed in the discovery paper by Soifer et al. (1984). Later excitement about the alternative possibility of enhanced star formation may have resulted in the somewhat premature conclusion that an appreciable fraction of infrared detected galaxies are "starburst" galaxies (e.g. de Jong 1986). In fact fig.2b suggests that only 10% of the galaxies in an infrared complete sample shows anomalously enhanced star formation ($L_2/L_1 > 10$). It is interesting to note that the two deviating galaxies (IRAS 0413+081 and IRAS 0414+001) are the most morphologically peculiar in the sample studied by Moorwood et al.. The one galaxy with $L_2/L_1 > 10$ among the RSA galaxies is NGC 2146, a well-known peculiar galaxy.

The fact that most of the mini-survey galaxies are probably anomalously

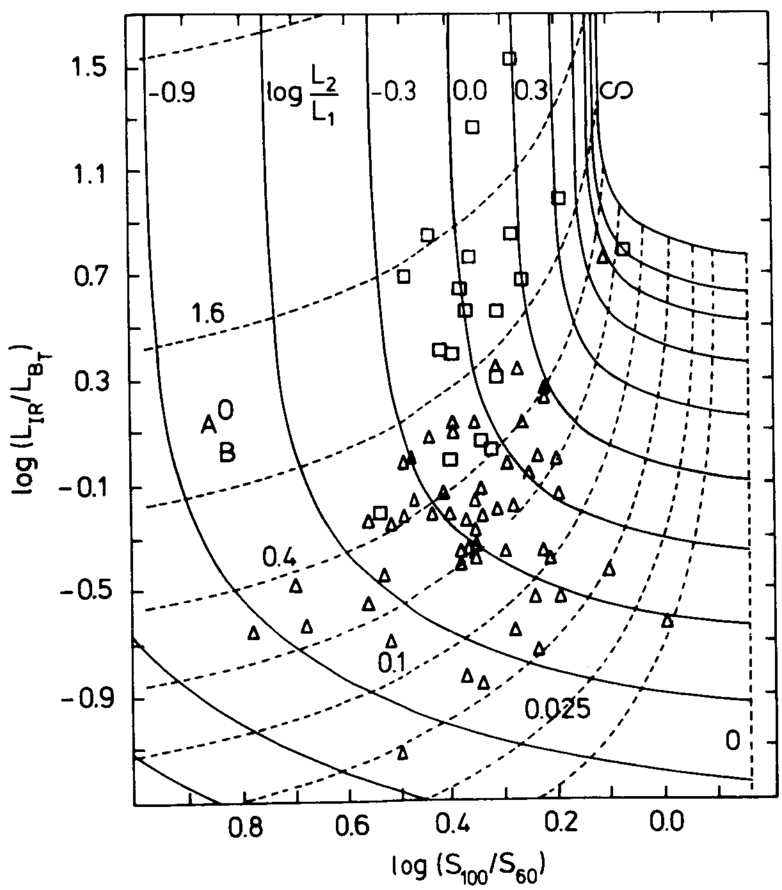

Figure 3. A theoretical L_{IR}/L_{B_T} versus S_{100}/S_{60} diagram. Lines of equal A_B^0 (dotted) and L_2/L_1 (full-drawn) are shown, calculated for a representative value of b/a = 0.6. As indicated by the labelling of these lines the values of the parameters increase by a factor two from one line to the next. Data points for bright optical RSA spirals (triangles) and mini-survey galaxies (squares) are plotted.

dusty was derived from near-infrared photometry by Moorwood et al. (1986). Our model analysis nicely confirms their findings.

Another way to illustrate our results is shown in the (L_{IR}/L_B) versus (S_{100}/S_{60}) diagram in fig.3 where data points for the optically complete RSA sub-set (triangles) and for the mini-survey sub-set (squares) have been plotted. Using our simple two-component model we have drawn lines of equal A_B^0 and L_2/L_1 in this diagram. These lines are calculated for a representative value of b/a = 0.6. For $A_B^0 > 1$ almost all optical radiation is reemitted in the infrared so that the ratio L_2/L_1 fixes the infrared color ratio S_{100}/S_{60} independent of the value of A_B^0, whereas L_{IR}/L_B is determined almost exclusively by the extinction. For small values of A_B^0 the quantity L_{IR}/L_B is most strongly dependent on L_2/L_1. The upper right hand corner in the diagram is forbidden because L_2/L_1 cannot exceed infinity.

Fig.3 clearly shows that the mini-survey galaxies are much more dusty than the optically selected bright RSA spiral galaxies while the star formation activity is only about twice as large in the mini-survey galaxies. It is quite rewarding that in spite of the simplicity of our model it is so remarkably succesful in explaining the differences between optically and infrared selected samples of galaxies. A more extensive discussion of our results will appear elsewhere.

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