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A Simple Model For Mid-Infrared Emission from Normal Galaxies

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Abstract. We have combined up-to-date stellar population synthesis models, a simple radiative transfer approach, and a fully comprehensive dust model with the aim of developing a simple but quantitative way of interpreting the mid-infrared spectra of galaxies. We apply these models to the observed correlations of mid-infrared luminosities (at 8 and 24 μm) with the star-formation rate of normal galaxies and find that the observations are naturally reproduced by our models. We further find that the observed 24 μm correlation places a weak constraint on relative distribution of dust and stars.

1. Introduction

Mid-infrared (mid-IR) emission from galaxies provides information on their energetics which is complementary to the far-infrared (far-IR) and arguably more useful. The reason for this is that the very small dust grains, which produce this emission, can be stochastically heated (Purcell 1976) by energetic photons, so that their peak temperatures are independent of their time-averaged temperatures, in which case the colour temperature of their emission is independent of the intensity of the radiation which heats them (Sellgren 1984). Consequently, when dust in this regime dominates the mid-IR luminosity of a galaxy, this luminosity, even when estimated from a narrow band filter, is an intrinsically weak function of the spatial distribution of the dust.

This has motivated us to develop a simple model for the infrared emission from galaxies, concentrating on those wavelengths where transient heating can dominate. Clearly, this requires an accurate treatment of transiently heated dust and so we use the state-of-the-art techniques presented by Draine & Li (2001), Li & Draine (2001) and Weingartner & Draine (2001). We make the connection to galaxy energetics by using STARBURST99 (Leitherer et al. 1999) simple stellar population models, and simple radiative transfer, to calculate the radiation field which is heating the dust.

2. Method

The modelling procedure we employ consists of three distinct parts: (1) Calculating the radiation field heating the dust, taking into account geometric effects and absorption by the dust; (2) Calculating the infrared radiation emitted by the dust; and, (3) Calculating the subsequent re-absorption of this infrared radiation by any further dust it encounters.

As mentioned above, we assume the dust to be heated by a single population of stars modeled using STARBURST99 (Vázquez & Leitherer 2005). Being interested primarily in the transiently heated regime, we consider a simple configuration in which the dust is in a geometrically thin spherical shell of radius R, with optical depth set by its total column density of hydrogen atoms n. The radiation field which heats the dust is calculated by assuming it to emanate from a central source and be isotropic and conserved at radii less than that of the dust shell. Absorption of radiation as it traverses the shell is taken into account although scattering is neglected. For consistency, the absorption cross section of the dust is derived from the same dust model used to calculate the emission from the dust. Although this model – a single heating source surrounded by a single dust shell – is a poor approximation to most normal star-forming galaxies, it is entirely equivalent to a more realistic model. If we alternatively assume star-formation to be distributed over N independent sites, each with an equal star-formation rate, and a dust shell at the same radius R, this is equivalent to putting all of the star-formation in a single region and the dust at an effective radius $R_{\rm eff} = R\sqrt{N}$.

The emission from the dust is calculated using the 'thermal-continuous' model of Draine & Li (2001) and the dust model parameters derived by Li & Draine (2001) and Weingartner & Draine (2001) for the local interstellar medium. The final stage of the model is to take account of the re-absorption of this emission by further dust. Here we make another simplification by assuming that if the total column density of the dust shell is n, then any emission from dust at a point with column density to heating source is n' will itself be attenuated by a further column density $n - n'$ before escaping the shell.

3. Results

To investigate the applicability of these models to real galaxies, we tested how well they reproduce the observed correlation between mid-IR luminosities and star-formation rates (as traced by extinction-corrected Hα luminosities) of galaxies in the *Spitzer* extragalactic First Look Survey (FLS) field (Wu et al. 2005). We repeated the analysis of Wu et al. (2005) to obtain K-corrected $8\,\mu$m and $24\,\mu$m dust luminosities and extinction and aperture corrected Hα data for these galaxies. We exclude galaxies dominated by active galactic nuclei by using the standard emission-line diagnostics. Model mid-IR luminosities were obtained by convolving our synthetic dust spectra (for a range of star-formation rates) with the *Spitzer* filter response curves. The Hα luminosities for the same range of star-formation rates were obtained by converting the ionising photon production rate from STARBURST99 stellar population models.

The results of this comparison are shown in Figure 1, which plots the observed data points on the mid-IR vs Hα luminosity plane, together with the best-fitting power law curve published by Wu et al. (2005, dashed line) and the expected model correlation for $R_{\rm eff} = 2\,$kpc (solid line). With the dust model parameters fixed to Galactic values, the only free parameter we consider in the models is $R_{\rm eff}$, the effective radius. We chose $R_{\rm eff} = 2\,$kpc for the models shown in Figure 1 as it yielded the best fit to the observed correlation. The effect that

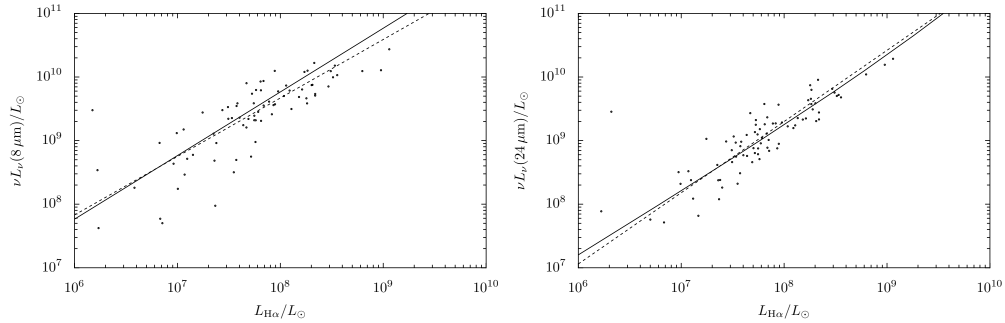

Figure 1. The correlation observed in the *Spitzer* FLS field between mid-IR and Hα luminosities (points), together with our models (solid lines) and the best-fitting power-law model of Wu et al. (2005, dashed lines). The left plot is for the IRAC 8 μm channel; the right for the MIPS 24 μm channel.

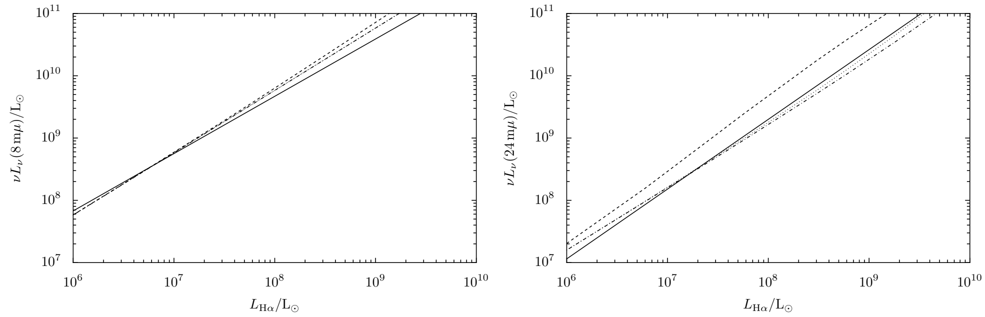

Figure 2. A comparison of the predicted dust luminosities (broken line styles) as a function of Hα luminosity and the observed best-fitting power-law correlation (solid line). The shell radii were 100 pc, 2 kpc and 5 kpc for the dashed, dotted and dash-dot-dash line styles respectively (the 2 kpc and 5 kpc traces essentially overlay each other). The left plot is for the IRAC 8 μm channel; the right for the MIPS 24 μm channel.

varying R_{eff} has on the model correlations is shown in the left and right panels of Figure 2 for the 8 μm and 24 μm mid-IR luminosities respectively.

4. Discussion and Conclusions

It can be seen from the model correlation between mid-IR and Hα luminosities, shown by the solid lines in Figure 1, that mid-IR luminosity is largely a linear tracer of the star-formation rate *if* all of the model parameters are constant, as would be expected for transiently heated dust. The figure also shows that the 8 μm luminosity is in theory more linear than the 24 μm luminosity. This is the case because multiple-photon heating of grains can be a significant source of emission at 24 μm at high star-formation rates.

It is, however, the comparison with real galaxies that is of most interest. In Figure 1, we also show the observed positions on the luminosity-luminosity plane of galaxies in the FLS as well as the best-fitting power-law curve of Wu et al.

(2005). Given the relative simplicity of the models we describe, the agreement with the data is remarkably good. In particular, we find that the constant of proportionality between mid-IR and Hα luminosities is easily reproduced by our models, which may be interpreted as evidence that transiently heated dust dominates mid-IR luminosities of galaxies and that most of the radiation produced by young stars is absorbed by the dust rather than escape the galaxy.

There is, however, a significant deviation between the data and the model for the $8\,\mu$m luminosity. At low Hα luminosities, some of the galaxies have much smaller mid-IR luminosities than would be expected from the model. This has been observed by Wu et al. (2005) and interpreted as due the now well-known deficiency of mid-IR emission from dwarf galaxies (e.g., Houck et al. 2004). There is also a trend for galaxies with *high* Hα luminosities to have smaller mid-IR luminosities then predicted by the model. This is reflected in the best-fitting power law of Wu et al. (2005) which has a slope smaller than one. This deviation is not reproduced by our models which have a slope close to one. The reason for the relatively low $8\,\mu$m emission from the most intensely star-forming galaxies is not clear. It may due to increasingly high obscuring column densities, causing the $8\,\mu$m mid-IR emission to become re-absorbed. Alternatively, it may be due to destruction of the smallest dust grains, e.g., those with radii around 3.5 Å to 5 Å, which dominate the emission at $8\,\mu$m.

In contrast, the correlation between the $24\,\mu$m and Hα luminosities appears to follow our model well at high Hα luminosities. The larger size of grains responsible for $24\,\mu$m emission makes it possible to place a constraint on the relative distribution of dust and the heating sources. Figure 2 shows that effective radii in the range 1–5 kpc give a good agreement with the observations. The implication is that the dust responsible for the bulk of $24\,\mu$m emission is not necessarily very close to regions of active star formation or very hot. The observed correlation is well reproduced by placing the dust relatively far from the heating sources.

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