

MODELLING THE SEDS OF SPIRAL GALAXIES

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Abstract. Modelling the UV/optical - infrared/submm SEDs of spiral galaxies observed with Herschel will be an essential tool to quantitatively interpret these observations in terms of the present and past star-formation activity of these systems. In this lecture we describe the SED modelling technique we have developed, its applications and tests of its predictions. We show that both the panchromatic SED modelling of individual galaxies and the B-band attenuation-inclination relation of large statistical samples suggest that spiral galaxies in the nearby Universe behave as optically thick systems in their global properties and large-scale distribution of light (central face-on B-band opacity of $\tau_B^f \sim 4$). However disk galaxies are very inhomogeneous systems, having both optically thick components (e.g. spiral arms), and optically thin components (e.g. the interarm regions), the latter making galaxies transparent to background galaxies.

1 Introduction

The measurement of star-formation rates (SFRs) and star-formation histories of galaxies - and indeed of the universe as a whole - requires a quantitative understanding of the effect of dust in attenuating the light from different stellar populations and how the absorbed stellar light is re-emitted by the dust in the infrared (IR). This can be achieved by modelling the whole spectral energy distribution of galaxies (SED), from the UV/optical to the far-IR (FIR)/submm. Thus, a SED model is a tool to translate observed SEDs of galaxies to their intrinsic properties, e.g. intrinsic distribution of stars and dust, opacity and SFRs. Such a tool will be crucial for the interpretation of data from the upcoming Herschel mission, which will continue the advancements in our knowledge of the FIR properties of galaxies (see reviews of Tuffs & Popescu 2004; Sauvage et al. 2005 or Sauvage 2007).

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From a technical point of view an SED model needs to incorporate a radiative transfer calculation for a realistic distribution of stellar emissivity and dust opacity. A variety of radiative transfer codes have been proposed in the literature: Kylafis & Bahcall (1987); Witt et al. (1992); Gordon et al. (2001); Bianchi et al. (1996); Baes & Dejonghe (2001a,b); Baes et al. (2005a,b); Jonsson (2006); Bianchi (2007), just to mention those which have been developed mainly for application to galaxies (e.g. Byun et al. 1994; Witt & Gordon 1996, 2000; Kuchinski et al. 1998, Ferrara et al. 1999, Pierini et al. 2004). A comprehensive review of the different methods used in these radiative transfer codes can be found in Kylafis & Xilouris (2005). Another key element that any SED model needs to incorporate is a dust model that would provide the optical properties of the dust grains and the grain size distribution. The standard dust models that have been used were those of Mathis, Rumple & Nordsieck (1977), Draine & Lee (1984), Dwek (1986), Désert et al. (1990), Laor & Draine (1993). More recently these models have been revised and updated by Weingartner & Draine (2001), Draine & Li (2001), Li & Draine (2001), Zubko et al. (2004), Draine & Li (2007). Radiative transfer and/or dust models can then be employed to model the SEDs of galaxies in different wavelength ranges: models which solely involve radiative transfer calculations have been used to account for the optical appearance of galaxies (Xilouris et al. 1997, 1998, 1999, Matthews & Wood 2001, Bianchi et al. 2007), techniques which solely involve dust models have been used to account for the FIR/submm SEDs (Dale & Helou 2002, Draine & Li 2007), and techniques which calculate the transfer of radiation in combination with a dust model have been used to self-consistently account for both the UV/optical and FIR/submm SEDs (Silva et al. 1998, Bianchi et al. 2000, Popescu et al. 2000). A review of the different modelling techniques can be found in Popescu & Tuffs (2005) for the case of spiral galaxies, which is the subject of this lecture. A review of the SED modelling of starburst galaxies can be found in Dopita (2005) and of dwarf galaxies in Madden (2005)(see also Madden 2007, this volume). In this lecture we illustrate the principles and techniques of SED modelling by describing the particular model we have developed (Popescu et al. 2000), together with selected applications.

2 Description of the model

Star-forming galaxies are fundamentally inhomogeneous, containing highly obscured massive star-formation regions, as well as more extended structures harbouring older stellar populations which may be transparent or have intermediate optical depths to starlight. Accordingly, our model divides the stellar population into an “old” component (considered to dominate the output in B-band and longer wavelengths) and a “young” component (considered to dominate the output in the non-ionising UV).

The “old” stellar population can be constrained from resolved optical and near-IR images via the modelling procedure of Xilouris et al. (1999). The procedure uses the technique for solving the radiation transfer equation for direct and multiply scattered light for arbitrary geometries by Kylafis & Bachall (1987). For edge-

on systems these calculations completely determine the scale heights and lengths of exponential disk representations of the old stars (the “old stellar disk”) and associated diffuse dust (the “old dust disk”), as well as a dustless stellar bulge. This is feasible for edge-on systems since the scale height of the dust is less than that of the stars. These calculations also determine the central face-on opacity ($\tau_B^{f,1}$) of the “old dust disk”. The calculation is done independently for each optical/NIR image, thus determining the extinction law for diffuse dust empirically.

The “young” stellar population is also specified by an exponential disk, which we shall refer to as the “young stellar disk”. Invisible in edge-on systems, its scale height is constrained to be 90 pc (the value for the Milky Way) and its scale length is equated to that of the “old stellar disk” in B-band. A second exponential dust disk - the “second dust disk” is associated with the young stellar population. The dust associated with the young stellar population was fixed to have the same scalelength and scaleheight as for the young stellar disk. The reason for this choice is that our thin disk of dust was introduced to mimic the diffuse component of dust which pervades the spiral arms, and which occupies approximately the same volume as that occupied by the young stars. This choice is also physically plausible, since the star-formation rate is closely connected to the gas surface density in the spiral arms, and this gas bears the grains which caused the obscuration. Because two disks of dust are required for the model, we refer to it as the “two-dust-disk” model. A schematic picture of these geometrical components of the model is given in Fig. 1, together with a mathematical prescription of the stellar emissivities and dust opacities used in the model.

The total UV output of the galaxy (expressed as the current star-formation rate (*SFR*)) and the central face-on opacity of the second dust disk ($\tau_B^{f,2}$) are the first two primary free parameters of the model to determine the FIR/submm radiation. They both relate to the smooth distribution of stars and dust in the second disk. A third primary parameter, F , is included to account for inhomogeneities in the distributions of dust and stars, in particular due to star-forming regions. By their very nature, star-forming regions harbour optically thick clouds which are the birth places of massive stars. There is therefore a certain probability that radiation from massive stars will be intercepted and absorbed by their parent clouds. This process is accounted for by the clumpiness factor F which is defined as the total fraction of UV light which is locally absorbed in the star-forming regions where the stars were born, giving rise to a local source of warm dust emission. Astrophysically this process arises because at any particular epoch some fraction of the massive stars have not had time to escape the vicinity of their parent molecular clouds. Thus, F is related to the ratio between the distance a star travels in its lifetime due to its random velocity and the typical dimensions of star-forming complexes. To conclude, in our formulation the clumpy distribution of dust is associated with the opaque parent molecular clouds of massive stars (see again Fig. 1 for a pictorial description of the diffuse and clumpy components of the model). In reality, some of the dust in the diffuse dust disks may also be in clumps without internal photon sources, but, provided these clumps are optically thin, the transfer of radiation through the disks will be virtually identical to that in a homogeneous disk. On

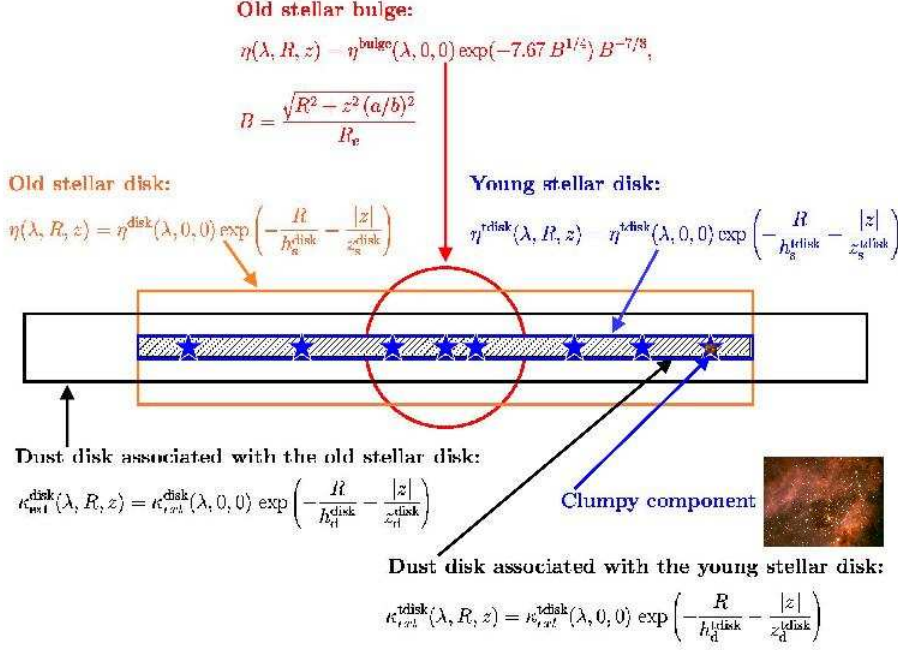


Fig. 1. Schematic representation of the geometrical distributions of stellar and dust emissivity used in the SED model of Popescu et al. (2000).

physical grounds, this condition will most often be met, since as soon as clumps become optically thick to the impinging UV light, they will lose their principal source of heating (the photoelectric effect) and will be prone to collapse and form stars (Fishera & Dopita 2007). This presumption is supported by the recent findings of Holwerda et al. (2007a,b), that the structure of the diffuse ISM consists of optically thin dusty clouds.

The attenuation of the light from massive stars by their parent molecular clouds has a different behaviour than the attenuation of their light by the diffuse component. One difference is that the attenuation by the parent molecular clouds is independent of the inclination of the galaxy. Another difference is that the wavelength dependence is not determined by the optical properties of the grains (because the clouds are so opaque that they block the same proportion of light from a given star at a given time at each wavelength), but instead arises because stars of different masses survive for different times, such that lower mass and redder stars can escape further from the star-forming complexes in their lifetimes. A proper treatment of the clumpiness factor is important since the clumpiness will change the wavelength dependence of the UV attenuation curves of star-forming

galaxies and will also affect the shape of the FIR SEDs.

After a further radiation transfer calculation (now incorporating the second dust disk) for the UV/optical/NIR light the heating of grains placed in the resulting radiation field can be determined. The illumination of the diffuse dust disks by optical/NIR photons is calculated by approximating the optical/NIR emissivity to that determined in the initial optical/NIR radiation transfer analysis, and is proportional to $SFR \times (1 - F)$ for the non-ionising UV. The FIR-submm emission from grains for trial combinations of $\tau_B^{f,2}$, SFR , F is then calculated for a grid of positions in the galaxy. As described in detail in Popescu et al. (2000) this calculation incorporates an explicit treatment of the temperature fluctuations undergone by small grains whose cooling timescales are shorter than the typical time interval between impacts of UV photons. This so-called “stochastic heating” process determines the amplitude and colour of the bulk of the diffuse emission from most spiral galaxies in the shortest wavelength bands ($< 100 \mu\text{m}$) of Herschel. Subsequently we integrate over the entire galaxy to obtain the FIR-submm SED of the diffuse disk emission. Prior to comparison with observed FIR-submm SEDs, an empirically determined spectral template for the warm dust emission from the star-forming regions, scaled according to the value of F , must be added to this calculated spectral distribution of diffuse FIR emission.

Due to the constraints on the distribution of stellar emissivity in the optical-near infrared (NIR) and on the distribution and opacity of dust in the “old dust disk” yielded by the radiation transfer analysis of the highly resolved optical-NIR images, coupled with the simple assumptions for the distribution of the young stellar population and associated dust, our model has just three free parameters - SFR , F and $\tau_B^{f,2}$. These fully determine the FIR-submm SED, and allow a meaningful comparison with broad-band observational data in the FIR/submm. As an example of a successful application of the model we show the model fit to the SED of NGC891 (Fig. 2). Further applications of the model can be found in Misiriotis et al. (2001). The models have been also generalised to predict the attenuation of stellar light (Tuffs et al. 2004) and the effect of dust on the observed scalelength and central surface-brightness (Möllenhoff et al. 2006) of disk galaxies as a function of inclination, wavelength and total central face-on opacity $\tau_B^f = \tau_B^{f,1} + \tau_B^{f,2}$.

3 The opacity derived from the SED modelling

The central face-on opacity derived from the SED modelling has two terms. The first term has a value $\tau_B^{f,1} \sim 1$, and characterises the optically thin component of a spiral galaxy, which is the interarm region of the disk, or the first disk of dust in our model. The second term has a value $\tau_B^{f,2} \sim 3$, and represents the effective optical depth of the dust in the spiral arms, if this dust were distributed in a thin disk - the second disk of dust in our model. Clearly the second disk of dust is not a real element, meaning that the dust is not smoothly distributed in this disk. Dasyra et al. (2005) and Bianchi et al. (2007) showed, as expected, that the second disk of dust of our model cannot have a smooth distribution, otherwise it would have been

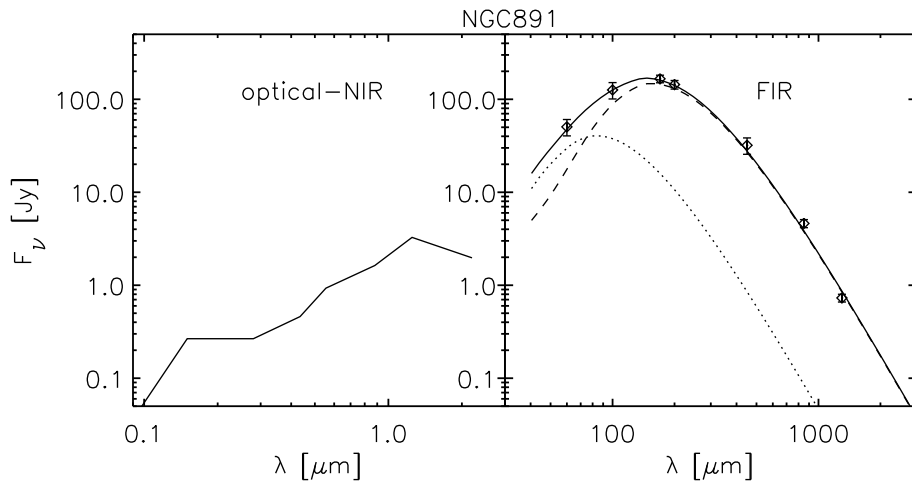


Fig. 2. The predicted SED of NGC 891 from the “two-dust-disk” model (Popescu et al. 2000).

seen as such in the near-infrared images of edge-on galaxies. The approximation would obviously not work if one needs to predict the detailed arm-interarm contrast of face-on systems. However approximating the spiral distribution with a second disk of dust seems to be a very good approximation for predicting the major observational characteristics of spiral galaxies, as demonstrated by the success of the model to pass several other observational tests.

4 Testing the models

4.1 The surface brightness distribution in the FIR/submm

We have seen that the model presented here can predict the optical appearance of galaxies and the integrated FIR/submm SEDs. But a more stringent test is to see if it can also predict the appearance of galaxies in the FIR/submm. In Fig. 3 one can see the comparison between the observed and predicted radial profiles of the diffuse component of NGC891 at 170 and 200 μm (Popescu et al. 2004). A very good agreement has been achieved between the observations and the model predictions. The small asymmetry in the observed profiles, at the level of about 10% of the total emission, is consistent with our model predictions for the emission from localised sources.

4.2 The attenuation-inclination relation

A fundamental test for our SED model is to see whether the typical solutions for the distribution of stars and dust and for the central face-on opacity needed to fit the panchromatic SEDs of individual galaxies can also predict the relation between

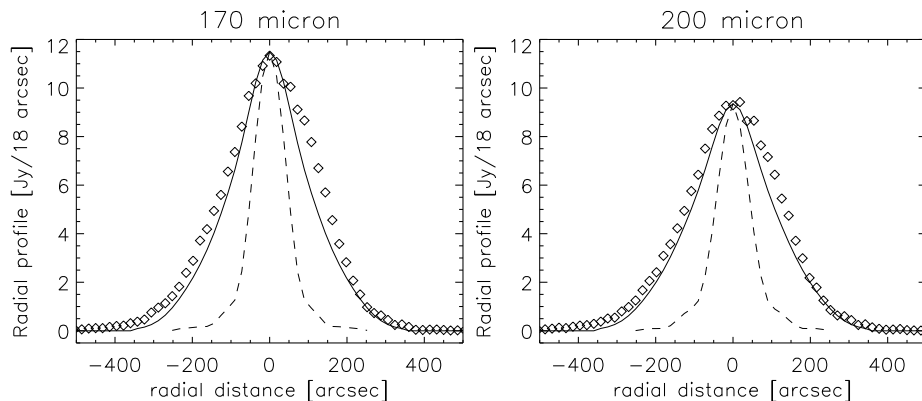


Fig. 3. Comparison between the observed (symbols) and predicted (solid line) FIR radial profiles of NGC891 (Popescu et al. 2004). The dotted lines represent the beam profile. The observations were done with the ISOPHOT instrument on board ISO. The predicted profiles are only for the diffuse component. The small excess emission in the observed profiles is likely to be due to localised sources.

optical attenuation and inclination derived from observations of large statistical samples of galaxies. This is an especially sensitive test, as the rise in attenuation with inclination will very strongly depend on the relative scaleheights of the assumed dust layers and stellar populations. In particular it is an independent test for the existence of the second component of dust represented by the second dust disk. Historically, there has been some debate as to whether studies of galaxies at various inclinations can be used to constrain the dust distribution and opacity simultaneously (Holmberg 1958; Disney, Davies & Phillipps 1989; Valentijn 1990; Disney et al. 1992). The general consensus was that one could not (see Davies & Burstein 1995). Now we are in the position to re-address such an analysis, since the distribution of stars and dust has already been constrained in our model from the optical and FIR data, and the attenuation-inclination relation can be used as a consistency check for the solution found from the SED modelling.

To this end we compared our model predictions with the B-band attenuation-inclination relation derived from the Millennium Galaxy Catalogue (MGC; Liske et al. 2003). The MGC is ideal for such an analysis due to its unique depth and spectroscopic completeness, and because all MGC galaxies have bulge-disk decompositions (Allen et al. 2006), which allowed the derivation of the attenuation-inclination relations separately for disks and bulges. These relations are shown in Fig. 4 together with the prediction from our SED model. One can see that the model predicts the data rather well. The best-fitting solution for the disks is for a central face-on opacity of $\tau_B^f = 3.8 \pm 0.7$, a solution that can simultaneously account for the attenuation-inclination relation of the bulge as well and is consistent with the solution found from the SED modelling of individual galaxies. Fuller details of this analysis are given in Driver et al. (2007).

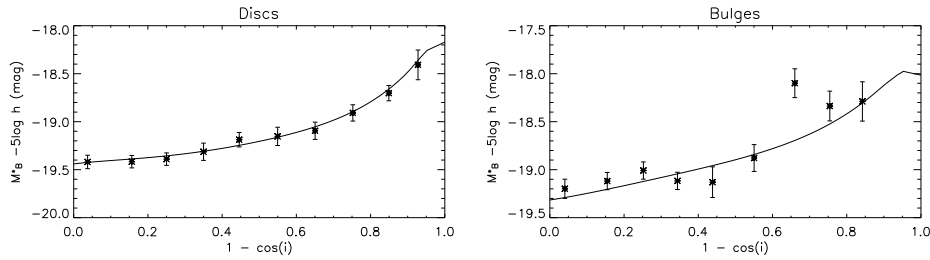


Fig. 4. The disk (left-hand panel) and bulge (right-hand panel) empirical attenuation-inclination relation derived from the MGC Survey compared to the prediction of the dust model of Tuffs et al. (2004) with a central face-on B-band opacity $\tau_B^f = 3.8$, as derived from the best-fitting solution for the attenuation-inclination relation for disks (Driver et al. 2007).

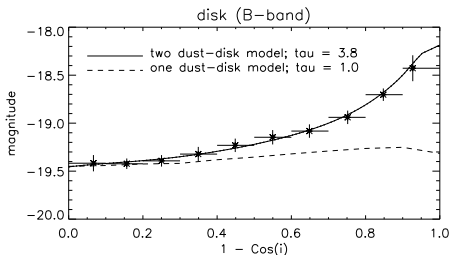


Fig. 5. Comparison between the predictions of the two dust-disk model (Popescu et al. 2000) with $\tau_B^f = 3.8$ (solid line) and of the one-dust disk model (Xilouris et al. 1997, Alton et al. 2004, Dasyra et al. 2005, Bianchi et al. 2007), with $\tau_B^f = 1$ (dashed line) for the attenuation-inclination relation for disks. The empirical attenuation-inclination relation derived from the MGC is plotted as symbols. One can see that the one-dust disk model fails to reproduced the observed data.

We should mention here that one of the strength of this test is that it is completely independent of the assumed dust emission properties. Thus the success of the solution found from the FIR/submm in predicting the attenuation-inclination relation should also remove the degeneracy between opacity and enhanced submm emissivity of the dust in the diffuse dust disks. In particular Alton et al. (2004), and Dasyra et al. (2005) have suggested that a solution with only one disk of dust and $\tau_B^f = 1$, as derived from fitting the optical images of edge-on galaxies (Xilouris et al. 1997, 1998, 1999, Bianchi et al. 2007), would still reproduce the FIR SEDs of galaxies if the dust emissivity were enhanced over what is assumed in typical dust models (e.g. Draine & Lee 1984). In Fig. 5 we plot the prediction for the attenuation-inclination relation of the model with one disk of dust and $\tau_B^f = 1$. One can see that this model fails to predict the steep rise in attenuation shown by

the data. This indicates that it is this second dust-disk, which mimics the dust in the spiral arms, that is needed to reproduce the FIR/submm SEDs of galaxies and the steep rise in attenuation with inclination.

5 Are spiral galaxies optically thin or optically thick?

The value of $\tau_B^f \sim 4$ obtained from both the SED modelling of individual galaxies and the attenuation-inclination relation of large statistical samples suggest that spiral galaxies behave as optically thick systems in their global properties. This is however fully consistent with the spiral disks having their interarm regions transparent to background galaxies (White et al. 2000). In other words the spiral disks are overall optically thick systems, but have an interarm component which is optically thin when viewed face-on.

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