Modelling the spectral energy distributions of galaxies

Richard J. Tuffs[1], Cristina C. Popescu[2,3], Nikolaos D. Kylafis[4,5]
[1] *Max-Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2] *The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Str., Pasadena, CA 91101, USA*
[3] *IPAC(Caltech/JPL), 770 S. Wilson Ave., Pasadena, CA 91125, USA*
[4] *University of Crete, P.O. Box 2208, GR-71003, Heraklion, Greece*
[5] *Foundation for Research and Technology-Hellas, P.O. Box 1527, GR-71110, Heraklion, Greece*

Abstract

We present results from a new modelling technique which can account for the observed optical/NIR - FIR/submm spectral energy distributions (SEDs) of normal star-forming galaxies in terms of a minimum number of essential parameters specifying the star-formation history and geometrical distribution of stars and dust. The model utilises resolved optical/NIR images to constrain the old stellar population and associated dust, and geometry-sensitive colour information in the FIR/submm to constrain the spatial distributions of young stars and associated dust. The method is successfully applied to the edge-on spirals NGC 891 and NGC 5907. In both cases the young stellar population powers the bulk of the FIR/submm emission. The model also accounts for the observed large-scale radial brightness profiles in NGC 891 as determined using the Infrared Space Observatory (ISO) at 170 & 200 μm and at 850 μm using SCUBA.

1 Introduction

Historically, almost all our information about the current and past star-formation properties of galaxies has been based upon spatially integrated measurements in the ultraviolet (UV), visible and near-infrared (NIR) spectral regimes. However, star-forming galaxies contain dust which absorbs some fraction of the emitted starlight, re-radiating it predominantly in the far-infrared (FIR)/sub-millimeter(submm) range. The true significance of this process even for "normal" (i.e. non-starburst) galaxies has been revealed by observations of a representative sample of late-type Virgo cluster galaxies with the ISOPHOT instrument on board the Infrared Space Observatory (ISO). These showed the dust emission to typically account for 50 percent of the bolometric output of these systems, with a spectral peak generally lying between 100 and 250 μm (Tuffs et al. 2002; Popescu et al. 2002).

In view of this, the measurement of current and past star-formation in galaxies - and indeed of the universe as a whole - requires a quantitative understanding of the role different stellar populations play in powering the FIR/submm emission. Here we present the results of a new modelling technique which can account for the observed optical/NIR-FIR/submm SEDs for dusty star-forming galaxies in terms of a minimum number of essential parameters specifying the star-formation history and geometrical distribution of stars and dust. Full details of the model and initial applications can be found in Popescu et al. (2000) and Misiriotis et al. (2001). In this paper we briefly overview the initial applications of this method, with emphasis on the predictions for the FIR/submm emission.

2 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) (also described elsewhere in this volume by Xilouris 2001). 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 process is feasible for edge-on systems since the scale height of the dust is less than that of the stars. 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. The emissivity of the "young stellar disk" is parameterised in terms of the current star formation rate (SFR) by relating the non-ionising UV emission to SFR using the population synthesis models of Bruzual & Charlot (2001) for $Z = Z_{\odot}$, a Salpeter initial mass function, a mass cut-off of $100\,\mathrm{M}_{\odot}$, and an exponential decrease of the SFR with time, with a time constant $\tau = 5\,Gyr$. A second exponential dust disk of grain mass $M_{\rm dust}$ - the "second dust disk" is associated with the young stellar population. This is needed to account for the observed submm emission from edge-on disk galaxies, which cannot be reproduced by models containing only the old dust disk determined from the optical images (Popescu et al. 2000, Misioritis et al. 2001). It is constrained to have the same scale length and height as that of the young stellar disk. Because two disks of dust are required for the model, we refer to it as the "two-dust-disk" model.

The current star-formation rate (SFR) and mass of the second dust disk ($M_{\rm dust}$) 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 the young stellar disk. F is defined as the fraction of non-ionising UV which is locally absorbed in HII regions around the massive stars.

The dust model corresponds to the graphite/silicate mix of Laor & Draine (1993) and the $a^{-3.5}$ grain size distribution of Mathis, Rumpl & Nordsieck (1977), which was found to be consistent with the extinction law determined from the optical/NIR images in all applications so far. After a further radiation transfer calculation 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 fixed according to the results of the 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 $M_{\rm dust}$, SFR, F is then calculated for a grid of positions in the galaxy, including an explicit treatment of stochastic heating. 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 HII regions, scaled according to the value of F, must be added to this calculated spectral distribution of diffuse FIR emission.

Due to the precise constraints on the distribution of stellar emissivity in the optical-near infrared (NIR) and 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 $M_{\rm dust}$. These fully determine the FIR-submm SED, and allow a meaningful comparison with broad-band observational data in the FIR/submm, where, in particular for distant objects, typically only a few spectral sample points for the spatially integrated emission are available. The parameters are strongly coupled, but in general terms, $M_{\rm dust}$ is principally constrained by the submm emission, $SFR \times (1-F)$ by the bolometric FIR-submm output and the factor F (in the absence of high resolution images) by the FIR colour.

3 Application to edge-on spiral galaxies

We first applied the above method to the well-known edge-on spiral galaxy NGC 891. This is one of the most extensively observed edge-on galaxies in the nearby universe, which makes it ideal for a verification of our modelling technique. We have also extended our SED modelling technique to four additional edge-on systems - NGC 5907, NGC 4013, UGC 1082 and UGC 2048 - with the aim of examining whether the features of the solution we obtained for NGC 891 might be more generally applicable. Here we mainly show and discuss the results for NGC 891, and only briefly illustrate the solution for NGC 5907.

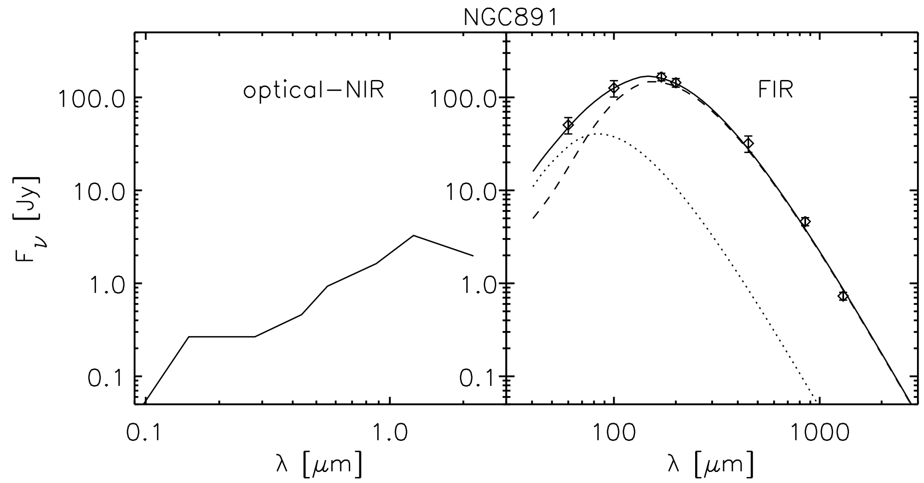

Figure 1: The predicted SED of NGC 891 from the "two-dust-disk" model with $SFR = 3.8\,{\rm M}_\odot/{\rm yr}$, $F = 0.22$ and $M_{\rm dust} = 7 \times 10^7\,{\rm M}_\odot$ in the second disk of dust. LH panel: the intrinsic emitted stellar radiation (as would have been observed in the absence of dust). RH panel: the re-radiated dust emission, with diffuse and HII components plotted as dashed and dotted lines, respectively. The data (integrated over $\pm 225''$ in longitude), are from Alton et al. 1998 (at 60, 100, 450 & 850 μm), Guélin et al. 1993 (at 1300 μm) and from Popescu et al. (2001) (at 170 & 200 μm).

The "two-dust-disk" model can successfully fit the shape of the SED for both NGC 891 and NGC 5907. The best solution for NGC 891 (Fig. 1) has an optical thickness $\tau^f_V = 3.1$ and a corresponding non-ionising UV luminosity $\sim 8.2 \times 10^{36}$ W. The luminosity of the diffuse component is 4.07×10^{36} W, which accounts for 69% of the observed FIR luminosity, and the luminosity of the HII component is 1.82×10^{36} W, making up the remaining 31% of the FIR luminosity. The best solution for NGC 5907 (Fig. 2) has a central face-on optical depth in the optical band $\tau_{\rm V} = 1.4$. The total FIR-submm re-radiated luminosity of NGC 5907, obtained by integrating

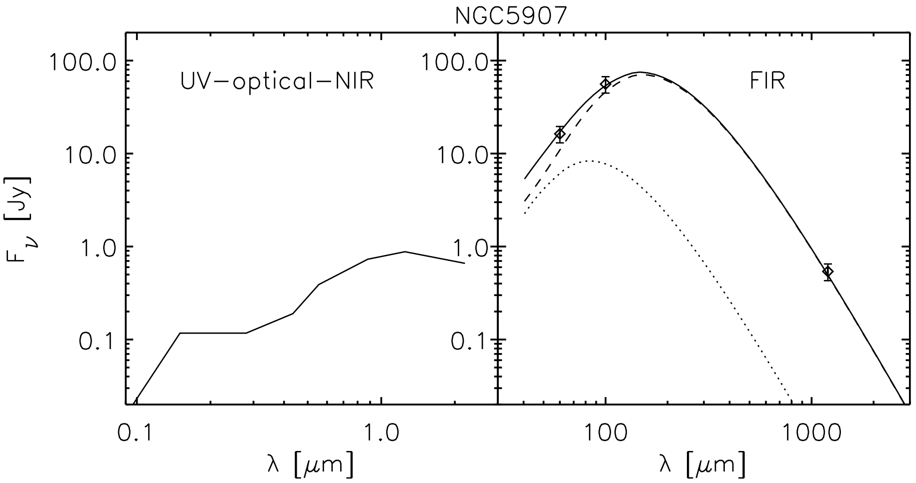

Figure 2: The predicted SED of NGC 5907 from the "two-dust-disk" model with $SFR = 2.2\,\mathrm{M}_\odot/\mathrm{yr}$, $F = 0.10$ and $M_{\rm dust} = 4.5 \times 10^7\,\mathrm{M}_\odot$ in the second disk of dust. The legend is as in Fig. 1. The data are from Young et al. (1989) (at 60 & 100 μm), and from Dumke et al. (1997) (at 1200 μm)

the "two-dust-disk" model SED, is 50.5×10^{35} W out of which 27.0×10^{35} W is attributed to heating from the young stellar population. Thus, about 40% of the dust emission is powered by the old stellar population. The major difference between NGC 891 and NGC 5907, on the basis of the "two-dust-disk" model, is that the spectrum of the former apparently allows for the existence of a larger contribution from HII regions (see Misiriotis et al. 2000 for a detailed discussion) - F takes values of 0.22 and 0.10, respectively. Such small values of F are expected for "normal" galaxies, in contrast to starburst systems, where the FIR/submm SEDs peak shortwards of 100 μm, and one would anticipate that F would be closer to unity.

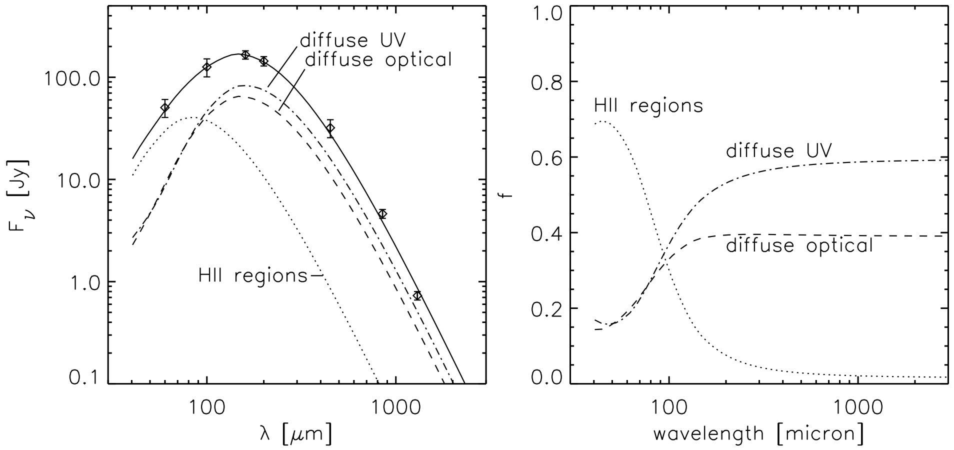

Figure 3: The absolute (LH panel) and fractional (RH panel) contribution of the three stellar components to the FIR emission versus wavelength for the "two-dust-disk" model. Dashed-line: diffuse optical radiation (4000 − 22000 Å); dashed-dotted line: diffuse UV radiation (912 − 4000 Å); dotted-line: HII regions. In the LH panel the total predicted FIR SED is given by the solid line. The data points are as for Fig. 1.

In both cases most of the luminosity comes from the diffuse component, and the main heating source is provided by the young stellar population. The relative contribution of optical and UV photons in heating the dust has been a longstanding question in the literature. Since we have a detailed calculation of the absorbed energy over the whole spectral range and at each position in the galaxy, we can

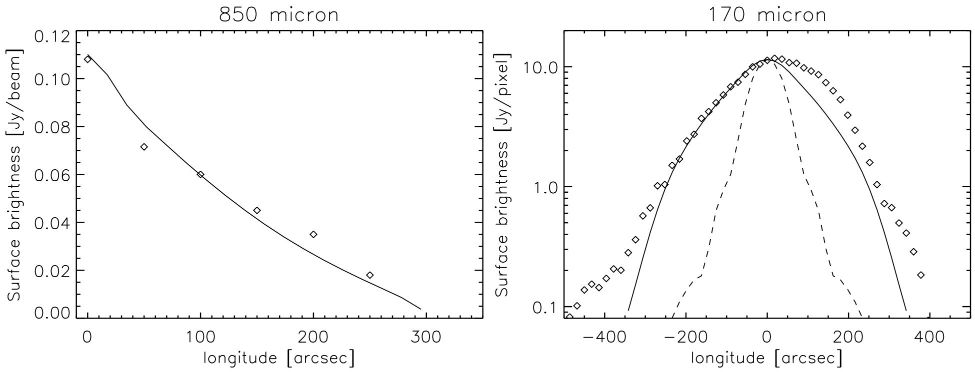

Figure 4: LH panel: The averaged radial profile of NGC 891 at 850 μm from the "two-dust-disk" model, plotted with the solid line. The profile is averaged over a bin width of 36″, for a sampling of 3″ and for a beam width of 16″, in the same way as the observed averaged radial profile from Alton et al. (2000) (plotted with diamonds). RH panel: the projected longitudinal profile (diamonds) observed by ISO at 170 μm (Popescu et al. 2001), with a common bin width and sampling interval of 18.4″. North is towards positive longitude. The solid line is the prediction from the "two-dust-disk" model and the dashed line the projected beam profile (FWHM 1.8 arcmin.)

directly calculate which part of the emitted FIR luminosity from each volume element of the galaxy is due to the optical and NIR photons, and which part is due to the UV photons. In this way we can also predict the contribution of different stellar populations in heating the dust as a function of FIR wavelength. Volume-integrated IR spectral components arising from re-radiated optical and UV light are presented in Fig. 3 for the case of NGC 891. We note that the diffuse optical radiation field makes only a relatively small contribution to the total emitted dust luminosity. This is in qualitative agreement with various statistical inferences linking FIR emission with young stellar populations, in particular the FIR-radio correlation. Our analysis predicts the predominance of UV-powered grain emission even in the sub-mm range, which, in turn, would predict a tighter FIR-radio correlation when the FIR luminosity integrated over the FIR-submm range is considered. This prediction has been recently confirmed by Popescu et al. (2002), using the new ISOPHOT observations of a complete sample of late-type Virgo cluster galaxies (Tuffs et al. 2002).

A more stringent test of the model is to compare its predictions for the morphology of the dust emission with spatially resolved maps. These are currently available only for NGC 891 amongst edge-on systems. Because observed radial profiles were derived by Alton et al. (2000) using the SCUBA observations at 850 μm, we first attempt to calculate the radial profiles at this wavelength and compare it with the observations (Fig. 4, LH), which are mainly sensitive to dust column density. We have found that in the case of the "two-dust-disk" model there is a very good agreement between the model predictions and the observations, where the observed profiles were mirrored for compatibility with the symmetry in our model. The predicted radial profile can be traced out to 300 arcsec radius (15 kpc), as also detected by the SCUBA.

Recent deep observations of NGC 891 with the ISOPHOT instrument at 170 and 200 μm (Popescu et al. 2001) offer a still sterner test of the model, as the profiles here depend on the distribution of both stellar luminosity and dust. Due to the larger longitudinal coverage of the ISO data, which embraces the outer, asymmetrical HI disk (Swaters et al. 1997), this time we did not mirror the observed profile. A very good agreement between the model prediction and the observed profiles can be seen in Fig. 4 (RH panel) for the Southern side of the galaxy. There is, however, an excess emission as compared to the model, in the northern side, which may be from a localised FIR source - probably a giant molecular cloud complex - associated with one of the spiral arms, and not considered by our model.

This may be a tentative indication that the template function for the HII regions may require an additional cold emission component to reflect the contribution of cold dust in the molecular clouds. A detailed analysis of radial colour profiles and a comparison of arm and interarm emission for resolved face-on spirals would help to resolve this issue in the future. There also seems to be an excess of FIR emission at radii larger than 300″, not reproduced by our model. We interpret this result as indicative of a dust disk larger than considered by our model, in which all dust disks are truncated at three scale lengths of the B-band stellar disk. A finer grid of models with varying truncation of the scale length may be needed to reproduce the faint FIR emission at large galactocentric radii.

4 Outlook

We have described a "two-dust-disk" model which can successfully account for the observed optical-FIR/submm characteristics of "normal" edge-on spiral galaxies in terms of three fundamental parameters - the SFR, F - the fraction of non-ionising UV absorbed locally in HII regions, and $M_{\rm dust}$ - the mass of a second dust disk associated with the young stellar population. Our model will also be applicable to face-on systems where the scale heights of the old stellar population and old dust disk cannot be so directly determined, making use of UV data as an additional constraint. Although our model requires resolved optical/NIR images to constrain the old stellar population and associated dust, it relies on geometry-sensitive colour information in the FIR/submm to constrain the spatial distributions of young stars and associated dust. The model will therefore be applicable to studies of cosmologically distant "normal" galaxies, which, though detectable, will be unresolved with forthcoming generations of spaceborne FIR observatories. It is to be expected that the optical-FIR-submm SEDs of these objects will differ systematically from their local universe counterparts, not only due to the presence of younger stellar populations, but also because of evolution of stellar disk thicknesses and changes in the dust abundance and composition.

References

Alton P. B., Bianchi S., Rand R. J., et al., 1998, ApJ, 507, L125
Alton P.B., Rand R.J., Xilouris E. M., et al., 2000, A&A, 356, 795
Bruzual, A. G., & Charlot, S., 2001, in preparation
Dumke, M., Braine, J., Krause, M., et al., 1997, A&A, 325, 124
Guélin, M., Zylka, R., Mezger, P. G., et al., 1993, A&A, 279, L37
Kylafis, N. D. & Bahcall, J. N., 1987, ApJ, 317, 637
Laor A., Draine B.T., 1993, ApJ 402, 441
Mathis, J. S., Rumple, W., Nordsieck, K. H., 1977, ApJ, 217, 425
Misiriotis A., Popescu C. C., Tuffs R.J . & Kylafis, D., 2001, A&A, 372, 775
Popescu, C. C., Misiriotis, A., Kylafis, N. D., Tuffs, R. J. & Fischera, J., 2000, A&A, 362, 138
Popescu, C. C., Madore, B. F., Tuffs, R. J., Kylafis, N. D., 2001, AAS198, 76.01
Popescu, C. C., Tuffs, R. J., Völk, H. J., Pierini, D., Madore, B. F., 2002, ApJ (in press)
Swaters, R.A., Sancisi, R. & van der Hulst, J.M. 1997, ApJ, 491, 140
Tuffs, R. J., Popescu, C. C., Pierini, D., Völk, H. J., Hippelein, H., et al., 2002, ApJS (in press)
Xilouris, E. M., Byun, Y. I., Kylafis, N. D., Paleologou, E. V., Papamastorakis, J., 1999, A&A, 344, 868
Xilouris, E. M., 2001 (this volume)
Young, J. S., Xie, S., Kenney, J. D. P., Rice, W. L., 1989, ApJS, 70, 699