The Evolution of Galaxies: an Infrared Perspective

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Abstract. Understanding the infrared emission of galaxies is critical to observational and theoretical investigations of the condensation of galaxies out of the intergalactic medium and the conversion of gas into stars over cosmic time. From an observational perspective, about half of all photons emitted within galaxies are locally absorbed by dust grains, necessitating a self-consistent analysis of the panchromatic emission of galaxies to quantify star-formation and AGN activity as a function of epoch and environment. From a theoretical perspective, physical processes involving dust are expected to play a major role in regulating the accumulation of baryons in galaxies and their condensation into stars on scales ranging from Mpc down to sub-pc. All this requires a quantitative analysis of the interaction between dust, gas and radiation. Here we review progress in the modelling of some of these processes.

INTRODUCTION

Traditionally, the presence of dust in galaxies has been regarded as a nuisance preventing a clear view of stars in galaxies. This is even more true if one is interested in newly formed stars, where dust is not merely a nuisance but a show stopper. This is not only due to the enhanced absorption probability of UV photons radiated predominantly by the young stars, but also because of the strong spatial correlations between young stars and gas and dust in galaxies. Fortunately infrared space astronomy is allowing us in a real sense to hunt for the dark and uncover the obscured star formation, since the stellar photons that are obscured by dust become visible in the infrared (IR). And in fact half of the energy emitted by all stars in the Universe since the Big Bang is absorbed by dust grains and is re-emitted in the IR, as revealed by measurements of the extragalactic background. So understanding dust emission is crucial to the understanding of the star-formation history of the Universe, which is intimately connected to the understanding of the conversion of gas into stars in galaxies over cosmic time.

At the same time dust can influence structure formation in the Universe through even more direct physical mechanisms affecting the thermodynamic state of gas inside and outside of galaxies, since dust is a primary coolant for the gas at all scales, in the intergalactic medium (IGM), in the interstellar medium (ISM) and in the star-forming clouds.

Here we shall review models for the conversion of stellar photons into infrared emission as well as recent progress in our understanding of dust as a main coolant for the gas. The first part is devoted to the mechanisms through which dust can affect the thermodynamic state of the gas from Mpc to pc scales. The second part describes recent progress in our ability to quantitatively model measurements of the amplitude and colours of dust emission to recover the nature of the stellar populations powering the infrared emission and other physical characterics of galaxies.

Previous reviews given on this topic can be found in [1, 2, 3, 4, 5, 6, 7].

DUST REGULATING THE THERMODYNAMIC STATE OF THE GAS

The intergalactic medium

One of the biggest puzzles concerning galaxy evolution and baryonic physics on scales of hundreds of kpc is the mechanism by which galaxies can accrete gas to fuel the ongoing star-formation in their disks. One observes in the Milky Way halo and around other massive galaxies cold infalling HI clouds but these galaxies are supposed to reside in hot virialized haloes and the nature of the thermal instabilities needed to cool gas from temperatures of $10^6 - 10^7\,$K (for the more massive haloes) is unknown. However it is sometimes forgotten that the most efficient way of cooling such a medium is not through bremsstrahlung or line emission in the Xrays, but through inelastic collisions of the hot electrons and ions with dust grains, providing there are some small quantities of grains in this medium (see [8]). Since collisional heating of dust grains is such an efficient mechanism, even trace quantities of grains can make a difference to the cooling for the gas, or at least trigger further cooling. These mechanisms have long been studied in the context of shocked interstellar gas (e.g. [10]) but it is only recently that it was realised that the effect of dust cooling should be considered in the context of structure formation.

This process has been recently investigated by [9], who derived cooling curves for the gas in the IGM with and without the presence of dust grains. Fig. 1 (left panel) shows their curves for different grain sizes and for a dust-to-gas ratio of 10^{-4} . At low temperatures, between $10^4 - 10^6\,$K, where the medium is not fully ionised, the cooling is dominated by atomic processes. For higher temperatures, $T > 10^6\,$K, where up to now bremsstrahlung was considered to be the most efficient cooling mechanism, it is shown that the dust is the dominant cooling factor. [9] also calculated how the ratio between infrared to X-ray dominated cooling changes as a function of the dust-to gas ratio. Fig. 1 (right panel) shows that for a dust-to gas ratio of 10^{-4} infrared cooling is more efficient for temperatures above $10^6\,$K, while for smaller dust-to gas ratios this condition applies at increasingly high temperatures.

The cooling functions described above have been coupled with numerical simulations for galaxy formation by [11]. Their simulations showed that although the differences between the two cases (in the absence and in the presence of dust) are not striking, the concentration of gas in the cool and high-density phase is higher when dust is included than in the purely gas cooling case.

To check whether these processes are operating in reality one should search for dust emission associated with X-ray emission in the transition regions between the cosmic web filaments and the star-forming disks of galaxies and ideal laboratories for this are clusters and groups. Thus far, the best and perhaps only example of a correspondence between FIR dust emission and X-ray emission from an IGM around galaxies is in

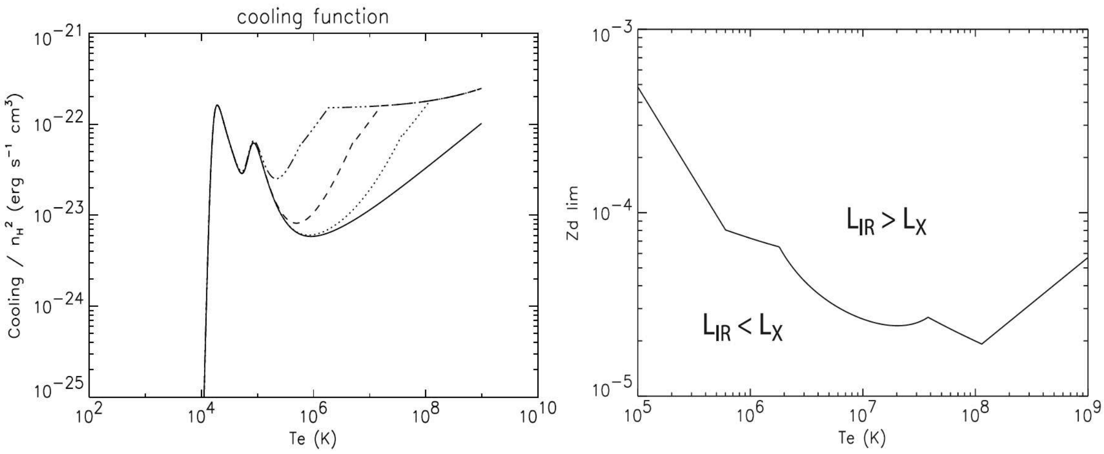

FIGURE 1. **Left**: Cooling curves for gas in the IGM without dust (solid line) and with dust (dotted and dashed curves for grain sizes of 0.5; 0.025 and 0.001 μm) from [9]. The intergalactic gas is modelled by a mixture of hydrogen and helium in cosmic proportion $X = 0.75$ and $Y = 0.25$, respectively, with a dust-to-gas ratio of $Z_d = 10^{-4}$ and without a background UV radiation field. The cooling is due to recombination, collisional ionisation, collisional excitation, bremsstrahlung and dust emission. **Right:** Infrared to X-ray dominated cooling in the parameter space dust-to-gas ratio Z_d and temperature of the gas, taken from [9].

Stephan's Quintet (SQ) (see [12, 13]), though it is unclear to what extent this correspondence is due to cooling instabilities in the IGM like those predicted in [9]. Recent spectroscopic observations of the SQ ([14]) have also shown that the pure rotational lines of hydrogen can be effective in cooling the IGM in the shock region of SQ. This was modelled as a multi-phase medium by [15].

The interstellar medium

Once inside galaxies, the subsequent evolution of the gas can be affected by grains in other ways. As is well known, dust grains heat the diffuse ISM via the photoelectric effect and the thermodynamical balance is maintained through an equality between the photoelectric heating and the FIR cooling lines which are powered by inellastic collisions with gas particles. Once the UV radiation field is suppressed, either by turning the sources off or by self-shielding by grains, the cooling is no longer balanced by heating, and the gas will condense further into denser structures, setting the seeds for condensation into dense molecular clouds.

In the simulation of [16] from Fig. 2 one can see the predicted ratio between [CII] and FIR within an individual simulated cloud, where the darker regions delineate more optically thick regions of the cloud where the UV photons can't penetrate but dust is still heated by the optical photons. Thus thermal pressure support can be reduced in density enhancement, potentially leading to further development of density contrast and ultimately affecting the propensity of gas to condense into stars. This shows again how dust is shaping the density structure of the gas, this time in the ISM.

The star-forming clouds

It is well known that, except for the very first generation of stars, the cooling needed

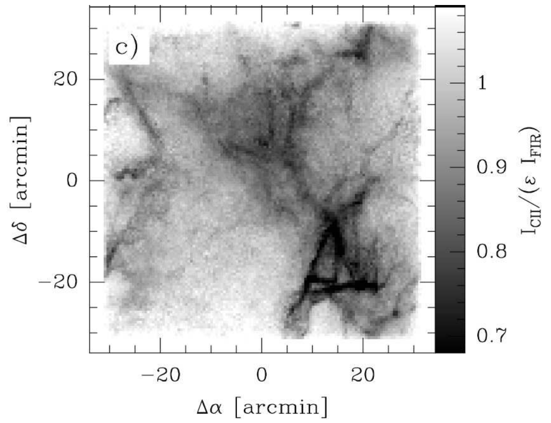

FIGURE 2. Simulated image of the ratio between [CII] and FIR within an individual cloud, from [16].

to precipitate the final stages of gravitational collapse in star-forming regions is provided by inelastic collisions of molecules with grains, visible through grain emission.

Thus we have arrived at a logical end point of a journey showing how dust physics might potentially influence the condensation of gas from the IGM into the ISM, then into denser structures within the ISM, and finally into cloud cores and stars. Now we have to set the target: - what are actually the star formation rates (SFRs) we have to ultimately explain through all these processes? This is presented in the next section, where we review recent techniques for modelling the conversion of stellar photons into infrared photons in galaxies, which are the tools for modelling the SEDs of galaxies to elucidate their physical parameters.

MODELLING THE SEDS OF GALAXIES

There are essentially two approaches to the problem of modelling the transfer of radiation in galaxies and the interaction between dust particles and photons. The first approach is to use multiwavelengths observations as a starting point and build models that can be directly applied to the panchromatic observations to decode their information. These are the SED model tools, which perform a direct translation between observed quantities and physical quantities, for example to derive intrinsic distributions of stellar emissivity and dust in galaxies and to derive intrinsic physical parameters like dust opacity and SFRs. Then the physical quantities can be compared with predicted physical quantities derived from theory. We call this process *decoding observed panchromatic SEDs*:

Observed SEDs –> Physical Quantities <–> Predicted Phys. Quantities <– Theory
| **|**
decode **compare**

A second approach is to start with a theory, in other words to assume “one knows how galaxies form”, and make predictions for some physical quantities, e.g. to use as a starting point a simulation of a galaxy instead of an observation. Subsequently a model that can deal with the dust physics and the transfer of radiation in the given simulation needs to be applied to obtain simulated panchromatic images of a galaxy for comparison with observations. The applied model is again a SED model tool, except that this works in the opposite direction from the previous approach. We call this process *encoding predicted physical quantities*:

Theory –> Predicted Physical Quantities –> Predicted SEDs <–> Observed SEDs

| **|**

encode **compare**

Obviously it is more difficult to decode than to encode. For example in the decoding process one needs to constrain the geometry of the problem, while in the encoding process the geometry is provided directly from theory. Nonetheless, the second approach relies on the assumption that the theory is correct, while in the first approach some geometrical components can be constrained empirically. Since both approaches are needed, we would like both approaches to converge towards a unique solution.

Decoding panchromatic SEDs

There are several essential steps included in any self-consistent model for the transfer of radiation and dust reprocessing. As mentioned before, one of the essential steps is the specification of geometry, which means the specification of the distributions of stellar emissivity and dust, both on kpc scales and on pc scales. Components that are seen through optically thin lines of sight can in principle be empirically constrained from high angular resolution optical observations. Those which are in very optically thick regime need to be fixed from physical considerations, with a posteriori consistency checks with data. Optically thin components are the old stellar populations in the disk or in the bulge. In edge-on galaxies [17] has shown that in the optical and NIR bands one can derive the scalelength and scaleheights of the disk stellar populations and associated dust, as well as the effective radius of the bulge stellar populations by fitting observed images with simulated images produced from radiative transfer calculations.

The geometry of young stellar populations and associated dust cannot be constrained directly from observations of direct stellar light, because young stars are highly obscured in most cases. From physical considerations we know that young stellar populations are born out of molecular clouds and therefore initially have small velocity dispersions and small scaleheights. Furthermore we expect a strong spatial correlation between the young stars and the dust associated with the parent molecular clouds. This situation has been modeled by [18] by distributing the stellar population in a thin exponential disk and the associated dust in a second layer which is also thin (small scaleheight) and occupies the same volume of space as the young stellar population.

Apart from specifying the geometry on kpc scales, an SED model needs to also take into account the absorption of radiation on pc scales, which arises from dust in the birth-clouds of massive stars. Because these clouds are spatially correlated with their progeny on parsec scales, they are illuminated by a strong UV-dominated radiation field of intensity 10-100 times that in the diffuse ISM. This gives rise to a localised component of emission from grains in thermal equilibrium with these intense radiation fields, which needs to be properly modeled. In principle one would then need to design a radiative transfer code that could operate from kpc down to pc scales. To date, the best resolution achieved with an adaptive grid code when modelling the observed SED of an individual galaxy is only 20 pc ([19]), much coarser than the required pc resolution.

For spiral galaxies we can circumvent this problem by making the assumption that the heating of the grains in the birth clouds is dominated by photons from their stellar progeny, and by neglecting any external contribution from the diffuse ambient radiation fields in the modelled galaxy. This should be an excellent approximation for spiral galaxies, where the filling factor of star-formation regions is small. In this case we can perform the radiative transfer calculations only for the diffuse component, and assume that a fraction $1-F$ of the radiation coming from the young stars in the birth clouds will escape their clouds and propagate in the diffuse component, but essentially no photon from the diffuse component will be absorbed by and heat the dust inside the clouds. This concept was introduced by the models of [20] and [18]. The low filling factor of opaque clouds in spiral disks assumed by this technique is supported by high resolution surveys of the Galactic Plane, e.g. the APEX Telescope Large Area Survey (ATLAS) of the Galaxy at 870 μm ([21]) . One should mention here that ATLAS is a very sensitive survey, going down to 50 mJy/beam, which is close to the $\tau = 1$ limit in the V band, thus ensuring that any optically thick cloud would be detected in this survey. By contrast, the distribution of the CO line shows a more diffuse distribution (see [22]), with large clouds overlapping and a very high filling factor. This is because the $^{12}C^{16}O$ line traces the optically thin outer surfaces of the molecular clouds, which is a different volume of space than that traced by the 870 μm emission. We therefore caution modellers of the SEDs of spiral galaxies not to follow the distribution of the CO emission when tracing the distribution of dust clumps which are optically thick in the UV/optical.

For starburst galaxies the approximation of a small filling factor for the star-formation regions is obviously no longer valid, and other procedures need to be invoked when modelling this type of galaxies. One way is to consider these galaxies as a collection of HII regions, as modelled by [23] with the updates from [24]. These models have a physical description for the evolution of the star-forming complexes and they also take into account collective effects due to merging of HII regions. However they still do not consider heating of the clumps by the external ambient radiation fields and do not have a diffuse component to contribute to the FIR emission. Another model proposed for starbursts is the hot spot model of [30]. This model considers star-forming clouds embedded in a diffuse radiation field, all within spherical symmetry, which is a reasonable assumption for starbursts. They also consider the heating of the clumps by the external radiation field, but this is not done in a self-consistent way.

Having specified the geometry of the problem the next step in any SED model is to run radiative transfer calculations (see [31] for a comprehensive review on radiative transfer techniques) to derive the radiation fields in galaxies. Fig. 3 (left panel) shows an example of calculated radial profiles in the plane of a typical spiral galaxy having a bulge-to-disk ratio $B/D = 0.33$. We note here the large variation in the colour of the radiation fields with position, which will introduce large differences in the shape of the

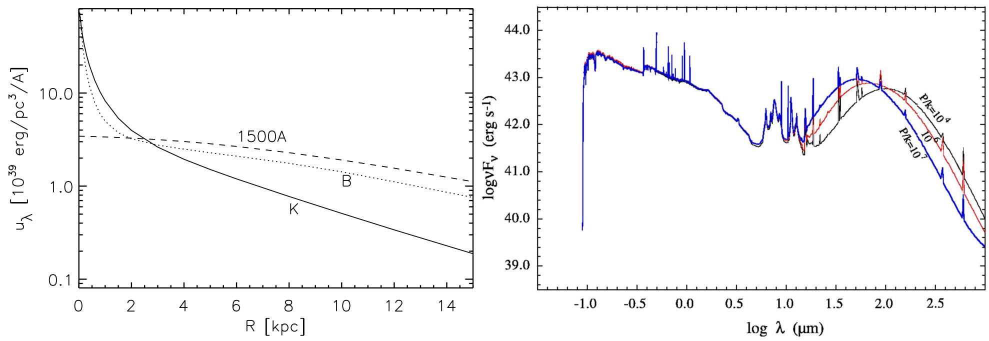

FIGURE 3. Left: Example of radial profiles of radiation fields (calculated using the model of [18]) in the plane of a typical spiral galaxy having a bulge-to-disk ratio $B/D = 0.33$. Right: Predicted SEDs for different pressure of the ambient interstellar medium, from [23].

FIR SEDs, as well as in the predictions about the role different stellar populations have in heating the dust as a function of position in the galaxy. Finally this will strongly affect the conclusions about the SFR and SF efficiencies in galaxies. Thus, models that assume radiation fields with the fixed colour of the local interstellar radiation fields (LIRF) are likely to introduce systematic uncertainties in the predictions for the dust emission SEDs and therefore for the conversion of gas into stars as a function of galactocentric radius.

Once radiation fields in galaxies are calculated one can derive the temperature distribution of grains of different sizes and composition as a function of position in the galaxy. Here it is important to recall that most of the grains in the interstellar medium are not heated in equilibrium with the radiation fields, but are heated stochastically. Fig. 4 shows examples of calculated probability distributions of temperature for grains of different sizes, composition and at different positions in a galaxy. The same grain sizes are plotted for each position and the calculation corresponds to a typical spiral galaxy having a $B/D = 0.33$. Overall small grains are more stochastically heated and therefore exhibit large temperature fluctuations while big grains emit at equilibrium temperature and therefore exhibit distributions close to or delta functions. Apart from the dependence on grain size, the temperature distributions also strongly depend on the intensity and colour of the radiation fields. One can see from Fig. 4 that big grains placed in the centre of the galaxy, where radiation fields are stronger and redder will emit close to equilibrium temperature, while the same grains placed in the weaker and bluer radiation fields in the outskirts of the galaxy will exhibit temperature fluctuations. This emphasises the need to have a self-consistent calculation, where the color and intensity of the radiation fields are calculated as a function of position in the galaxy.

The spatially integrated dust and PAH SEDs can then be obtained by integrating over all positions in a galaxy. We first show the predictions for the diffuse component in spiral galaxies, using the model of [18], where the parameters of interest are: dust opacity (τ_B^f), luminosity of the young stellar populations (SFR), luminosity of the old disk stellar populations (old) and B/D. Fig. 5 shows SEDs where one parameter at a time is varied, all the others being fixed to the values corresponding to the best fit of NGC 891. The main effect of increasing opacity is to increase the overall amplitude of the dust and PAH emission SEDs, with a fast increase for the optically thin cases and a slower increase

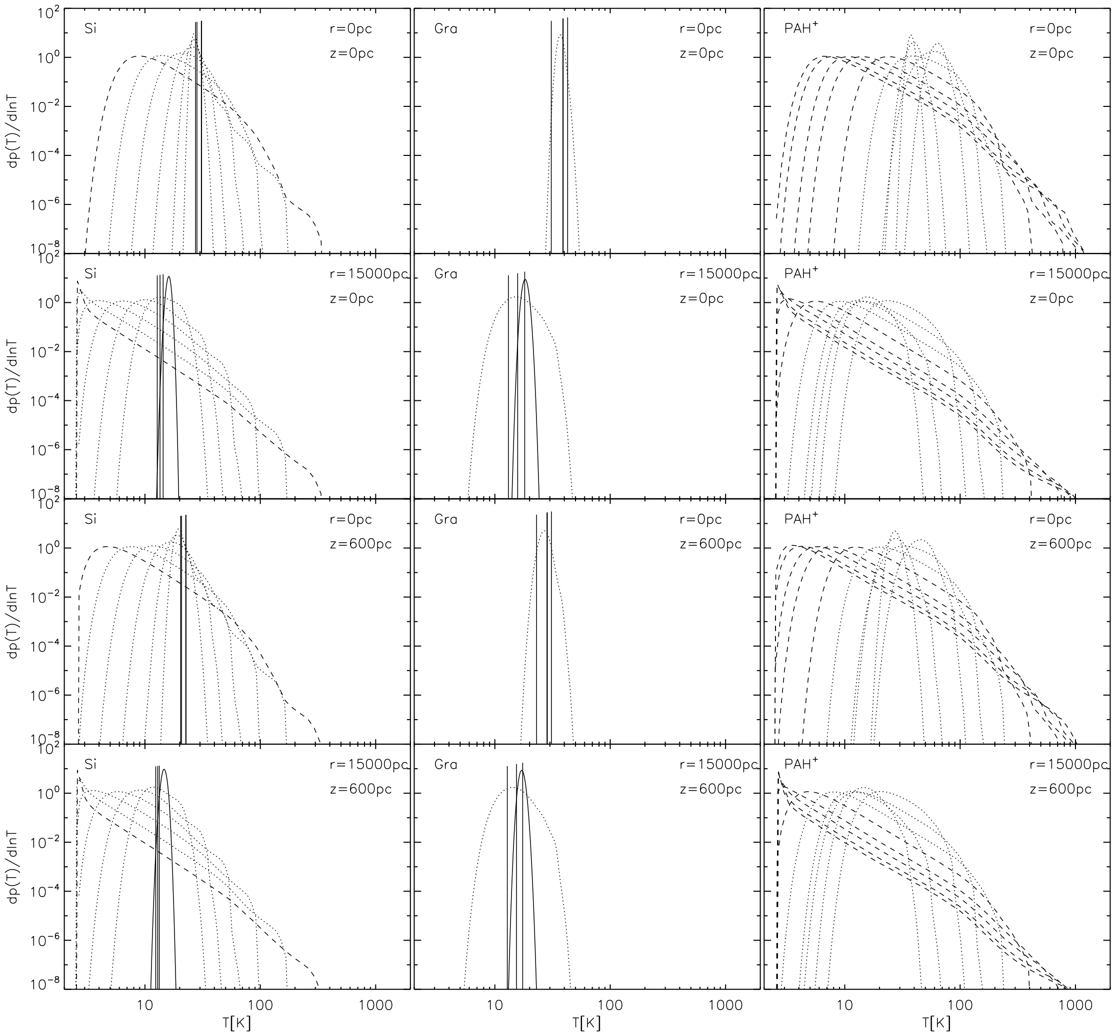

FIGURE 4. Temperature distributions for dust grains of different sizes (plotted as different curves in each panel) and various composition: Si (left panels), Gra (middle panels) and PAH^+ (right panels), heated by the diffuse radiation fields. The calculations were done for a typical spiral galaxy having a bulge-to-disk ratio $B/D = 0.33$ and using the model of [18]. Temperature distributions for PAH^0 are not plotted in this figure. Dashed lines are for grains with radius $a < 0.001\,\mu$m (0.00035, 0.00040, 0.00050, 0.00063 and 0.00100 μm), dotted lines are for grains with $0.001 < a \leq 0.01$ (0.00158, 0.00251, 0.00398, 0.00631, 0.01000μm) and solid lines are for grains with $a > 0.01$ (0.0316, 0.10000, 0.31623, 0.7943 μm). The biggest grains have delta function distributions, since they emit at equilibrium temperature. Going from the top to the bottom panels the calculations are done for different positions in the model galaxy: $r = 0$ pc, $z = 0$ pc; $r = 15000$ pc, $z = 0$ pc; $r = 0$ pc, $z = 600$ pc; and $r = 15000$ pc, $z = 600$ pc.

and eventually a saturation for the optically thick cases. We note here that the opacity is the only parameter that changes the submm level. Essentially one cannot increase the level of submm emission by just increasing the luminosity of the heating sources. The effect of increasing the *SFR* is to produce warmer SEDs, both because the peak of the SEDs shifts towards shorter wavelengths, but also because the ratio between mid-infrared (MIR) and FIR increases. An increase in the contribution of the old disk stellar

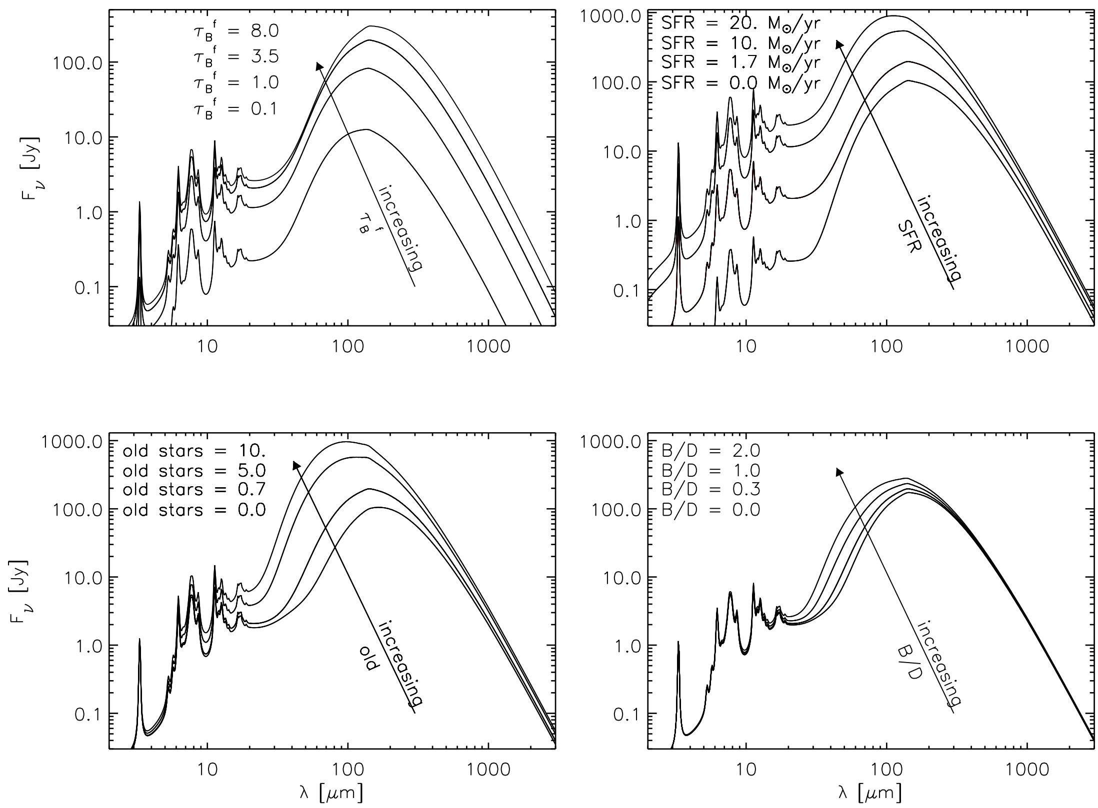

FIGURE 5. Spatially integrated dust and PAH emission SEDs of the diffuse component calculated using the model of [18]. Each panel shows the effect of changing one parameter of the model at a time, while the other parameters are kept fixed to the value corresponding to the best fit of NGC 891.

population *old* produces a similar shift of the peak of the FIR SEDs towards shorter wavelengths, but the amplitude of the MIR/PAH emission does not increase accordingly, as the PAH are mainly excited by the UV photons predominantly produced by the young stellar population. The variation in the B/D produces very similar changes in the IR SEDs to those produced by the variation in the disk old stellar populations, but with a small dynamic range. Overall the ratio between the PAH and FIR emission will be highly dependent on the ratio of the old to young stellar populations.

From the trends in Fig. 5 one can see that overall the 4 parameters of the model are fairly orthogonal and it is therefore possible to decode the FIR SEDs in a fairly non-degenerate way. Of course one would need to add the clumpy component to the diffuse one to obtain the total infrared SEDs, and this would add another parameter (F - the clumpiness factor in the model of [18]). However, the optical and UV data need also to be added when trying to decode the panchromatic SEDs. Thus, the corresponding predictions for attenuation of stellar light ([25], but see also [26] for alternative models) should be used in conjunction with the dust emission SEDs in order to obtain final solutions. The derived values of opacity can then be used to correct surface-brightness (SB) photometry of stellar light for the effect of dust using corresponding models (see [27]). Alternative methods for obtaining dust opacities rely on statistical determinations (e.g. [28]); see [29] for studies of dust corrected SB photometric parameters.

Lets now consider the total IR emission from starburst galaxies. In the model of [23] (see also [24]) the infrared emission is taken to be exclusively emitted by dust in PDR regions at the interface of HII regions with their parent molecular clouds. The main factor controlling the shape of the dust emission SED is then the radius of the PDRs, which is larger for lower density, low pressure environments, and smaller for high density, high pressure environments. In Fig. 3 (right panel) one sees the effect of changing ambient pressure from $P/k = 10^4\,\mathrm{cm}^{-3}\,\mathrm{K}$ (ambient medium of a spiral galaxy) to 10^6 through $10^7\,\mathrm{cm}^{-3}\,\mathrm{K}$ (ambient medium of a starburst). The PDR is closer to the exciting stars for the higher pressure environment and thus the dust emission is warmer for this case.

In the model of [30], the IR emission is emitted by a combination of clouds with embedded stars and a diffuse dusty intercloud medium. Thus, the temperature of the dust emission depends not only on the compactness of the clouds, but also on the opacity of the diffuse intercloud medium and the overall luminosity density of the stars. [30] showed the effect of increasing the illumination of dust in the diffuse medium by either increasing the number of stars or by decreasing the radius of the starburst region or by decreasing the opacity of the diffuse medium. By contrast, the effect of changing the size of the clumps (done in this model by a density parameter), was found to be quite small.

In conclusion, different models invoke different physical mechanisms to change the illumination of grains in starburst galaxies. The main difference relates to the relative importance of the clumps and diffuse interclump medium, and better observational constraints are needed to pin down this issue.

Encoding predicted physical quantities

As mentioned before, the second approach to modelling the SEDs of galaxies is that of encoding predicted physical quantities. In most cases this entails using simulated images of galaxies as input for dusty radiative transfer codes to predict the appearance of these images as would be seen through dust and also to predict the dust emission images - see [32, 33]. For example [32] uses the same approximation for the treatment of the clumpy component as that used in the models that decode the observed SEDs of spiral galaxies (see [20] and [18]). Thus, [32] makes the assumption that the illumination of the birth clouds is dominated by emission coming from the embedded stars, and considers the radiative transfer only for the diffuse component, while the clumpy component is treated separately, using the model of [24]. So in this way the local absorption on pc scales is dealt with.

In this approach the geometry does not need to be specified, since it is provided by the simulations. The use of simulations has the advantage to provide quite spectacular images of galaxies (see Fig. 6). However, because of the high resolution required to produce all the structure provided by the simulations, explicit calculation of the radiation fields is not performed, as this would add an extra dimension to the overall calculation, and make them intractable. Since radiation fields are not calculated, self-consistent

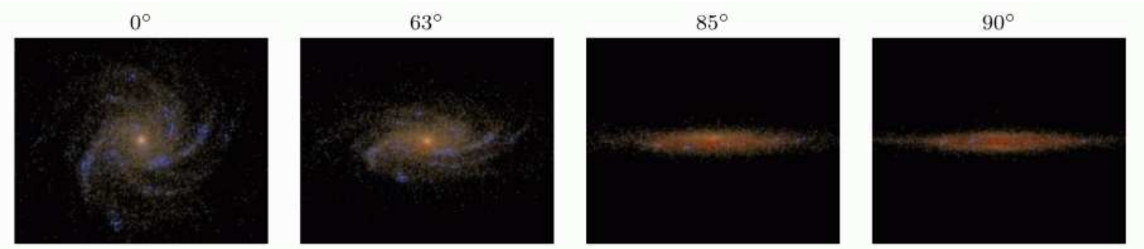

FIGURE 6. Simulated images of a dust attenuated galaxy seen at different inclinations, from [32].

calculations of the stochastic heating of the small grains and PAH molecules cannot be performed. In the model of [32] the phenomenological model of [34] is used instead to re-radiate the emission from stochastically heated grains.

Here we have attempted to give a broad classification of the different approaches to the SED modelling of galaxies. It was our intention to introduce general concepts rather than cover detailed models in the literature. A more complete list of SED models also includes: [35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47], where here we did not include models for AGN tori.

OUTLOOK

One of the biggest challenge for the SED models is to make them applicable to the large statistical samples of panchromatic data that are now becoming available for the local universe galaxies, like for example the GAMA survey ([48]), the Herschel ATLAS survey ([49]) and GALEX ([50]). In the future we will also need to re-calibrate our SED models to make them applicable to the distant universe, using data from the next generation observatories, like SPICA ([51]), ALMA, JWST and VLT. At the same time we will need to include dust physics in the simulations for galaxy formations within a fully cosmological context. Realistic simulations of disk galaxies are now being for the first time produced (see [52]) and, within a few years, we expect this to be routinely done. It is therefore crucial to incorporate all known physics related to sources and sinks of grains in galaxies and in the surrounding IGM, as well as the cooling and heating mechanisms involving grains. Only then we will be able to make reliable predictions, which will directly constrain theories for the formation and evolution of galaxies.

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