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OBSERVING AND MODELLING THE DUST IN NEARBY GALAXIES

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Abstract. Dust grains are a crucial ingredient in the interstellar medium of galaxies. They are efficient at absorbing and scattering UV/optical photons and then reradiating the absorbed energy in the infrared/submm wavelength range. The amount and spatial distribution of dust in galaxies can hence be investigated in two complementary ways: by its attenuation effects at short wavelengths, and by its thermal emission at long wavelengths. Both approaches have their advantages and challenges. We discuss a number of recent interesting results on interstellar dust in nearby galaxies. We particularly focus on the role of dust radiative transfer, which has advanced considerably in the past few years, and the wealth of observational results provided by the Herschel Space Observatory.

1. INTRODUCTION

Although dust only makes up a small part of the interstellar material (typically 1% in mass), its impact on the other baryonic components in galaxies should not be underestimated. For example, dust particles act as a catalyst for the formation of molecular hydrogen, regulate the heating of the neutral gas component through photoelectric heating and inelastic interactions, and provide shielding for molecules from the UV radiation of young stars. On galaxy-wide scales, interstellar dust affects our view on galaxies: on average, about 30 to 50% of the starlight in the Universe is absorbed by interstellar dust grains, and converted to FIR/submm emission (Xu & Buat 1995; Popescu & Tuffs 2002; Davies et al. 2012). It is hence important to carefully trace and map the dust in galaxies of different types and in different environments.

Broadly speaking, the dust in galaxies can be traced in two ways. The first is by studying the thermal emission of the dust at FIR and submm wavelengths. The advantage of this technique is that the dust emission is usually optically thin, such that it is relatively easy to translate FIR/submm luminosities to dust masses. The main disadvantages are that FIR/submm observations need to be done from space with cryogenically cooled instruments, and that the unfavourable diffraction limit results in fairly poor spatial resolution. An alternative method that does not suffer from poor spatial resolution consists of carefully modelling the attenuation effects of the dust on the stellar emission in the optical window. The main problem with this approach is that translating attenuations to dust masses is complex and subject to many different effects (e.g., Disney et al. 1989; Witt et al. 1992; Baes & Dejonghe 2001).

In this contribution we discuss some of the progress that has recently been made in our understanding of the distribution and characteristics of interstellar dust in nearby galaxies. We particularly focus on the role of dust radiative transfer (which has advanced considerably in the past few years), and the observational leap forward provided by the Herschel Space Observatory.

2. ATTENUATION BY INTERSTELLAR DUST

2. 1. DUST RADIATIVE TRANSFER

One of the ways to investigate the amount and spatial distribution of interstellar dust in galaxies is by analysing its effect on the starlight at UV and optical wavelengths. The proper way to do this is by means of radiative transfer calculations that take into account the relevant effects (absorption and multiple anisotropic scattering) in a realistic geometrical setting.

3D radiative transfer is generally considered to be one of the grand challenges in computational astrophysics (Steinacker et al. 2013). The main reason is that the underlying physical processes combine, in the stationary case, to a nonlocal and nonlinear 6D problem. The radiative transfer equation is an integro-differential equation that is usually nonlinearly coupled to other equations. Solving such a high-dimensional nonlocal, nonlinear problem requires substantial computational resources, affecting the solution algorithms and potentially limiting the model complexity.

In spite of the difficulties described above, significant progress has been made in the past decade, with an increasing number of codes capable of dealing with the complete 3D dust radiative problem. The vast majority of the codes that can handle the 3D dust radiative transfer problem today are based on the Monte Carlo technique (e.g., Gordon et al. 2001; Baes et al. 2003, 2011; Jonsson 2006; Bianchi 2008; Robitaille 2011; Camps & Baes 2015), with only a few other codes based on pure ray-tracing solvers (Steinacker et al. 2005; Natale et al. 2014). Both methods face the challenges of grid discretisation, determination of uncertainties in solutions, and accurate comparison between observations and the model calculations. Still, the future of 3D dust radiative transfer is bright, with a growing number of people actively involved, a continual refinement/improvement of existing codes, and the development of new codes and algorithms.

2. 2. SIMULATING THE EFFECTS OF EXTINCTION

One of the long standing questions in extragalactic astronomy is how much dust affects the apparent photometric properties of galaxies, such as apparent scale lengths,

Figure 1: Mock face-on (top row) and edge-on (bottom row) views for two simulated galaxies, in which the effects of dust attenuation are fully taken into account. The left panels correspond to the Renaud et al. (2013) simulation, the right column is the Eris simulation (Guedes et al. 2011). The three-colour images are based on the r, g and u band images produced by the SKIRT radiative transfer code (Baes et al. 2003, 2011). Figure taken from Saftly et al. (2015).

surface brightnesses, luminosities, axial ratios, etc. This has been investigated through radiative transfer modelling with varying degrees of sophistication and geometrical realism. Byun et al. (1994) were the first to convincingly demonstrate that effects of scattering are often counter-intuitive and crucial to properly interpret the effects of dust. With the increase of computing power, these results have gradually been refined (e.g. Pierini et al. 2004; Tuffs et al. 2004). In general, it was found that the importance of dust attenuation varies as a function of wavelength, galaxy inclination and star-dust geometry.

An example of one such study is the work by Gadotti et al. (2010). They used radiative transfer simulations to create mock images of dusty galaxies, and subsequently applied 2D bulge/disc decomposition techniques to this set of models. Rather surprisingly, the effects of dust on the structural parameters of bulges and discs obtained from 2D bulge/disc decomposition cannot be simply evaluated by putting together the effects of dust on the properties of bulges and discs treated separately. Dust effects were found to be more significant for the bulge parameters than for the disc parameters, and, combined, they lead to a strong underestimation of the bulge-to-disc ratio up to a factor of two in the V band, even at relatively low galaxy inclinations and dust opacities. Similar results have been obtained by Pastrav et al. (2013a,b).

In recent years, N-body/hydrodynamical simulations have started to successfully reproduce the observed characteristics of spiral galaxies (Governato et al. 2009; Agertz et al. 2011; Guedes et al. 2011; Renaud et al. 2013; Marinacci et al. 2014). The spatial resolution of these simulations is sufficient to resolve both large- and small-scale inhomogeneities. The combination of such models with powerful 3D radiative transfer codes that can handle complex geometries thanks to advanced grids (Niccolini & Alcolea 2006; Saftly et al. 2013, 2014; Camps et al. 2013) opens up the possibilities to investigate the systematic effects of dust on the observable properties of galaxies in a realistic setting. This combination is particularly useful in the frame of large-scale cosmological hydrodynamical simulations, in which large numbers of galaxies of different types are formed that should ideally reflect the present-day Universe (Vogelsberger et al. 2014 Schaye et al. 2015). Given the significant effects of dust attenuation, 3D radiative transfer codes play a crucial role in this comparison process (Figure 1).

2. 3. RADIATIVE TRANSFER MODELLING OF NEARBY GALAXIES

Radiative transfer codes are powerful tools to systematically investigate the effects of attenuation on galaxy models. Often, however, we are interested in the dust content of a specific galaxy based on a set of UV/optical/NIR images, and a radiative transfer code by itself, no matter how advanced, is not sufficient to achieve this. This so-called radiative transfer modelling of galaxies is an inverted problem that requires the combination of a radiative transfer code and an optimisation procedure. Several fitting codes have been set up that combine a radiative transfer code with an optimisation algorithm (Xilouris et al. 1997; Bianchi 2007; Schechtman-Rook et al. 2012). All too often, however, this optimisation procedure is neglected and chi-by-eye models are presented as reasonable alternatives.

Edge-on spiral galaxies have been a preferred class for radiative transfer modelling, as the dust shows nicely as a thin dust lane. The pioneering work in this field by Kylafis & Bahcall (1987) and Xilouris et al. (1997, 1998, 1999) showed that dust is generally distributed in an extended and thin disk, with modest optical depths that would make the galaxies completely transparent if they were to be seen face-on. These results were confirmed by Bianchi (2008). De Geyter et al. (2013, 2014) recently combined a 3D Monte Carlo code with an optimisation library based on genetic algorithms into a code that can simultaneously fit arbitrary 3D models to a set of UV/optical/NIR images. This "oligochromatic" fitting has clear advantages over standard monochromatic fitting, as it can minimise the degeneracies that are hard to overcome when radiative transfer models are fitted to one band only. Applying this technique to a set of 12 edge-on spiral galaxies, De Geyter et al. (2014) find results that are on average consistent with previous results, although the median face-on optical depth is larger than in these previous studies (Figure 2).

3. THERMAL EMISSION BY INTERSTELLAR DUST

3. 1. HERSCHEL AND NEARBY GALAXIES

Besides modelling the attenuation in the optical regime, the dust in galaxies can also be traced by its thermal emission in the infrared. IRAS, ISO and Spitzer allowed us to study dust emission up to about 200 μm, butwere rather limited in spatial resolution.

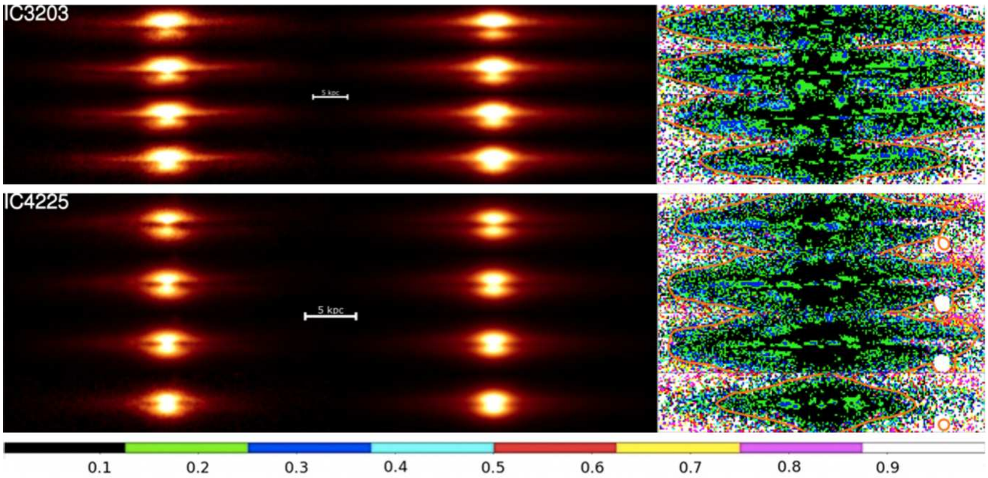

Figure 2: Results of the oligochromatic FITSKIRT radiative transfer fits to two edge-on spiral galaxies, from De Geyter et al. (2014) In each panel, the left-hand column represents the observed images in the g, r, i and z bands (from top to bottom), and the middle column contains the corresponding fits in the same bands. The right-hand column contains the residual images, which indicate the relative deviation between the fit and the image. A colour bar with the scaling of the latter is indicated at the bottom.

The Herschel Space Observatory (Pilbratt et al. 2010) opened a new window on the FIR/submm spectral domain, allowing us to probe the cold dust component in a large number of nearby objects. During its lifetime from 2009 to 2013, Herschel observed hundreds of nearby (and distant) galaxies with its two imagers, PACS (70–160 μm) and SPIRE (250–500 μm), with an unprecedented angular resolution and sensitivity.

Many Herschel key and normal programmes were devoted to nearby galaxies. A number of these were targeted surveys that focused on different samples of nearby galaxies (e.g., Boselli et al. 2010; Kennicutt et al. 2011; Verstappen et al. 2013; Madden et al. 2013). Other projects were blind surveys that mapped large areas of extragalactic sky, which can be used to investigate the dust properties of nearby galaxies (and galaxies at higher redshift) in a more statistical way (e.g., Davies et al. 2010; Eales et al. 2010). Covering all the achievements and results of these various programmes is an impossible task. We therefore select just a few remarkable results, and refer to e.g. Dunne et al. (2013) for more results and references.

One of the major achievements of Herschel on nearby galaxies is a solid characterisation of the cool dust budget of galaxies of different types and in different environments. The Herschel Reference Survey (Boselli et al. 2010) has imaged more than 300 stellar-mass-selected galaxies and allowed to investigate the dust scaling relations along the Hubble sequence (Cortese et al. 2012; Boselli et al. 2012; Smith et al. 2012a). It was found that the dust-to-stellar mass ratio anti-correlates with stellar mass, stellar mass surface density and NUV$-r$ colour, and decreases significantly when moving from late- to early-type galaxies. These scaling relations are similar to those observed for the atomic gas fraction, supporting the idea that the cold dust

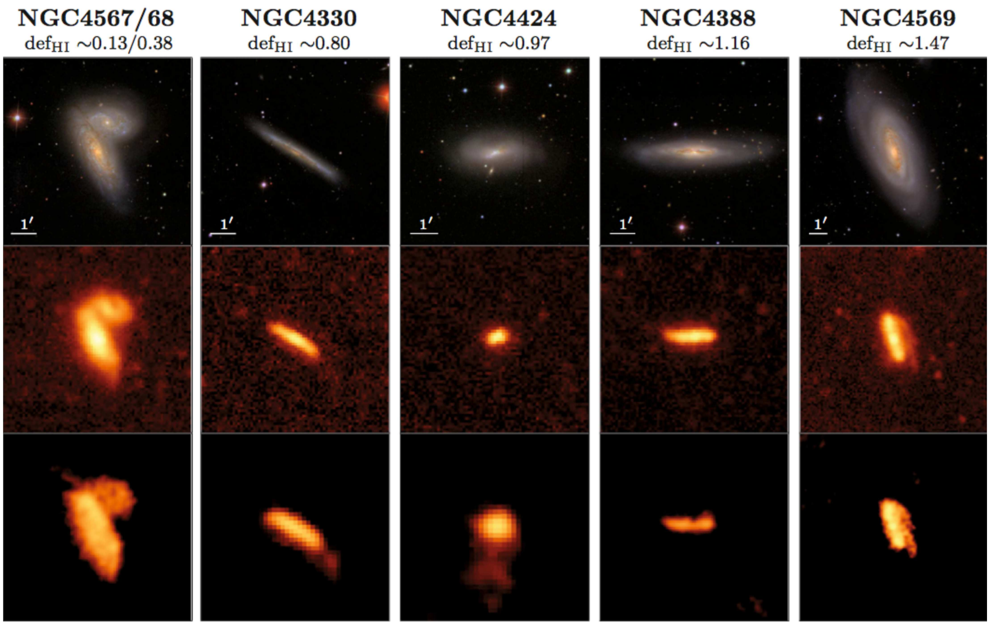

Figure 3: A comparison of the distribution of stars (top), cold dust (center) and atomic gas (bottom) in five Virgo Cluster galaxies. The galaxies are ordered from left to right according to HI deficiency. The extent of the dust disk is significantly reduced in HI-deficient galaxies, suggesting that the cluster environment is able to strip dust as well as gas (Cortese et al. 2010b).

is tightly coupled to the cold atomic gas component in the interstellar medium (see also Groves et al. 2015). Studying galaxies in the Virgo Cluster, clear evidence was found that dust can be efficiently removed from galaxies in a cluster environment (Cortese et al. 2010a,b; Gomez et al. 2010; Figure 3). Interesting trends were also found comparing populations of high- and low-metallicity galaxies. The dust characteristics and the gas-to-dust ratio alter substantially when going from high to low metallicity; these differences derive from a complex interplay between stellar mass, metallicity and star-formation activity (Madden et al. 2013; Rémy-Ruyer et al. 2014, 2015).

The superior spatial resolution of Herschel also enabled studies of the distribution and heating sources of dust in nearby galaxies, and many prototypical galaxies were examined in detail (e.g., Bendo et al. 2010, 2012; Baes et al. 2010b; Boquien et al. 2011; Aniano et al. 2012; Mentuch Cooper et al. 2012; Foyle et al. 2012; Parkin et al. 2012; Hughes et al. 2014). One of the most spectacular and iconic images of the Herschel mission is the 5.5 × 2.5 deg^2 FIR/submm image of the Andromeda galaxy, taken in the frame of the HELGA programme (Fritz et al. 2012). Even at the sparsest Herschel resolution (36” at 500 μm), physical scales of only 140 pc are resolved. Smith et al. (2012b) show that the gas-to-dust ratio appears to increase as a function of radius, from ∼20 in the centre to ∼70 in the star-forming ring at 10 kpc. This apparent radial variation can be explained by a similar metallicity gradient. Viaene

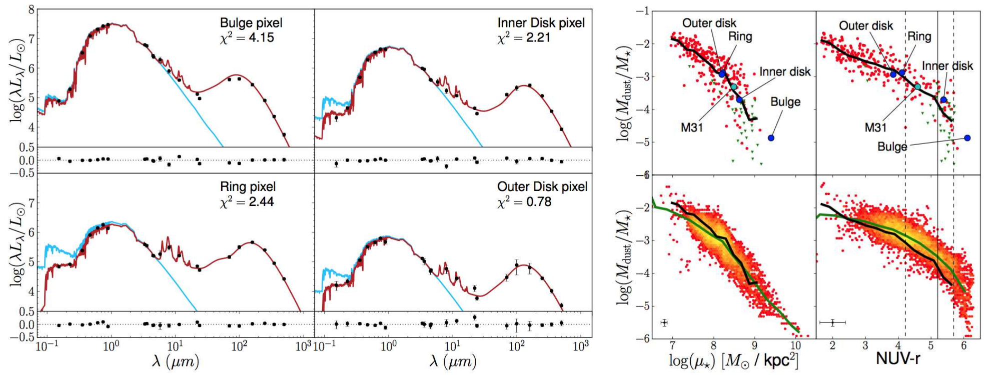

Figure 4: Left: panchromatic SED fits to four individual 36" pixels in different regions of M31. In each pixel, a physically motivated SED model is fitted to the observed fluxes. Right: a comparison of the dust scaling laws between the HRS galaxies (top panels) and the individual pixels in M31 (bottom panels). The similarity strongly suggests that these are in situ correlations, with underlying processes that must be local in nature (Viaene et al. 2014).

et al. (2014) modelled the panchromatic SED of M31 on sub-kpc scale, and found strong correlations between the dust-to-stellar mass ratio and various other properties, in particular the NUV$-r$ colour and the stellar mass surface density. Striking similarities with corresponding relations based on integrated galaxies (Cortese et al. 2012) are found, strongly suggesting that these are in situ correlations, with underlying processes that must be local in nature (Figure 4).

3. 2. PANCHROMATIC RADIATIVE TRANSFER MODELLING OF NEARBY GALAXIES

The availability of radiative transfer codes that can self-consistently model the attenuation and thermal emission by dust in 3D geometries opens up the possibility of dust energy balance studies of nearby galaxies. As the starlight that is absorbed by dust grains in the UV/optical/NIR region is re-emitted in the MIR/FIR/submm wavelength regime, one would expect the absorbed luminosity to be equal to the total thermal luminosity. Accounting for thermal emission in radiative transfer codes is a major complication, as the exact form of the thermal emission term usually depends on the intensity of the radiation field itself in a complicated and nonlinear way (Steinacker et al. 2013). It becomes extremely complex when the dust medium contains very small dust grains, including PAHs. Different approaches have been developed to calculate the emission spectrum due to very small grains and PAHs, and this has been built into several radiative transfer codes, using various approximations and/or assumptions (Misselt et al. 2001; Juvela & Padoan 2003; Baes et al. 2011; Camps et al. 2015).

Panchromatic radiative transfer modelling has mainly been applied to a number of edge-on spiral galaxies (Misiriotis et al. 2001; Alton et al. 2004; Bianchi 2008; Baes et al. 2010a; Popescu et al. 2011; MacLachlan et al. 2011; De Looze et al. 2012a,b; Schechtman-Rook et al. 2012), which have the advantage that the extinction and emission of dust can easily be observed along the line-of-sight, and that the dust can

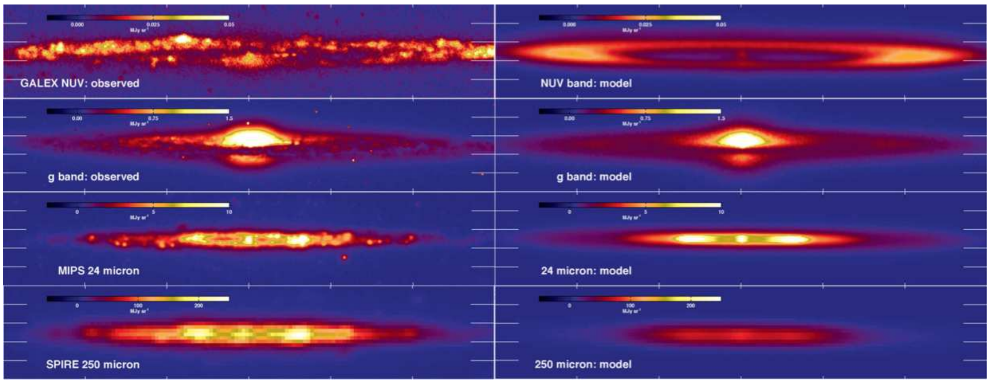

Figure 5: SKIRT dust radiative transfer modelling of the edge-on spiral galaxy NGC 4565 by De Looze et al. (2012b). The panels in the left-hand column are the observed GALEX NUV, SDSS g, MIPS 24 μm and SPIRE 250 μm images. The panels on the right-hand column are the corresponding radiative transfer model fits. The model reproduces the UV, optical and MIR images well, but underestimates the FIR/submm emission substantially.

be vertically resolved and traced out to large radii. The predicted FIR fluxes of self-consistent radiative transfer models that successfully explain the optical extinction generally underestimate the observed FIR fluxes by a factor of about three (Figure 5). The most preferred explanation for this energy balance problem is that a sizeable fraction of the FIR/submm emission arises from additional dust that has a negligible extinction on the bulk of the starlight, such as young stars deeply embedded in dusty molecular clouds. The presence of compact dust clumps can boost the FIR/submm emission of the dust while keeping the extinction relatively unaltered.

Recently, the first efforts have been undertaken to expand panchromatic dust radiative transfer modelling to face-on spirals galaxies. The complex morphology visible in face-on disk galaxies, in combination with the computational cost of the full radiative transfer treatment, makes this a challenging task. De Looze et al. (2014) present a full panchromatic radiative transfer model for M51, in which the dust geometry is constrained through the FUV attenuation. The model successfully reproduces the observed SED and the observed images from UV to submm wavelengths, and shows that young stellar populations provide two thirds of the energy for heating the dust.

Given the availability of extensive multi-wavelength imaging data sets and state-of-the-art 3D radiative transfer codes, more panchromatic radiative transfer modelling of galaxies of different types and in different environments can be expected in the near future.

4. SUMMARY AND CONCLUSIONS

This contribution can be summarised as follows

- Dust is an important ingredient of the interstellar medium. It can be traced by its attenuation effects on the starlight, or by its direct thermal emission at infrared and submm wavelengths. Both approaches have their advantages and challenges.

- Recent years have seen an enormous progress in the field of 3D dust radiative transfer, thanks to an increase in computing power, the development and maturing of different algorithms, and a wealth of multi-wavelength data. The Monte Carlo technique is the most popular and developed approach.
- Toy model studies indicate that the effects of absorption and scattering on the physical properties of galaxies are complex and sometimes counterintuitive. Hydrodynamical galaxy simulations become increasingly realistic, and 3D dust radiative transfer post-processing is important to compare the results of these simulations to the observed Universe.
- The Herschel Space Observatory revolutionised FIR/submm astronomy, and enabled for the first time to trace the dominant cold dust budget in galaxies across the Hubble sequence and in different environments. The dust scaling relations seem similar at the global and the local scale, which suggests that they are in situ correlations driven by local processes.
- Thanks to the coupling of radiative transfer codes to optimisation routines, detailed radiative modelling of individual galaxies has become possible. Most of the efforts so far have concentrated on edge-on disk galaxies, where an inhomogeneous dusty ISM needs to be invoked to reconcile the dust seen in attenuation and in emission.

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