
Infrared dust emission
from nearby galaxies:
radiative transfer simulations
and *Herschel* observations

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Cover:

- *Background:* Combined *Herschel*/XMM image of M31 (from the HELGA observations). Image credit: ESA/Herschel/SPIRE/PACS/HELGA/J. Fritz, UGent; ESA/XMM-Newton/EPIC/OM/W. Pietsch, MPE.
- *Top right:* Approximate true-colour image (*top*) and MIR/FIR/sub-mm false-colour composite (*bottom*) representing the stellar radiation and dust extinction, respectively dust emission in a simulated spiral disc galaxy viewed almost edge-on (inclination $i = 85^\circ$), using the SKIRT dust radiative transfer code.
- *Bottom left:* The *Herschel Space Observatory*. Image credit: ESA.

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Introduction

1

1.1

The importance of dust in the ISM

Interstellar dust (e.g. Mathis 1990; Krügel 2003; Draine 2003a, 2004; Dwek 2005; Draine 2009a,b; Compiègne 2010; Demyk 2011) plays an important part in the physics and chemistry of a galaxy's interstellar medium (ISM), composed of the gas and dust interspersed between the stars, even though its contribution to this ISM is only about 1% in terms of mass. Roughly the same mass fraction of the contents in molecular clouds consists of grains of interstellar dust, mostly smaller than 1 micrometre in diameter, thus more resembling smoke particles rather than grains of sand found on Earth. Their main chemical components are carbons and silicates, not necessarily both present in a single dust grain (Jones 2000).

In the late phases of a massive star's life, metals¹ are expelled into the ISM. This happens through stellar winds during the main sequence phase, the supergiant phase and especially during the supernova phase. The same is done by less massive stars during their final evolutionary stages, e.g. as asymptotic giant branch (AGB) stars. As these metals venture further into the surrounding interstellar space, the radiation from their stars of origin becomes ever weaker and they cool down, until the point where they can actually aggregate into small complexes and thus form microscopic dust particles (Draine 2003a, 2004; Dwek 2005; Compiègne 2010).

When the first high-mass stars in a molecular cloud are formed, they produce intense ultraviolet (UV) radiation and blow away the gas in their immediate surroundings, even ionising the gas of the molecular cloud and then pushing it away through their radiation pressure and stellar winds. The interstellar dust present in cloud fragments which are still contracting and have not formed stars yet, shields these fragments from this UV radiation preventing their dissociation (Compiègne 2010). At an even earlier stage of the ISM life cycle, the dust also gives a contribution to the regulation of heating and cooling in the ISM of photodissociation regions, e.g. at the edges of giant molecular

¹ In astronomy, any element with a higher atomic number than helium's is considered a metal.

clouds (Draine 2004). Further into the star formation, much like the molecules in a gas cloud, dust particles in it can cool the contracting cloud by transforming kinetic energy into photons, by radiating away the increased thermal energy, emitting in the infrared.

Dust particles have another important part in interstellar clouds, since they can act as catalysts for the transformation processes turning the atomic into molecular hydrogen, as well as forming (much) more complex molecules, offering reaction sites on their surfaces (Draine 2003a, 2004, 2009a; Compiègne 2010).

In the past, dust was mostly considered a nuisance, as it absorbs and scatters UV and optical radiation, rendering the correct interpretation of optical data rather difficult. The dust was first identified as the source of reddening by Trumpler (1930) and Lindblad (1935). Over the past few decades up to the present, it has become a subject of scientific research in its own right, studying its properties through the exact behaviour previously regarded as impeding, i.e. the absorption and scattering of UV and optical radiation.

As longer wavelength, mainly red, light is less affected by this extinction (the combination of absorption and scattering) than shorter wavelength photons, dust makes objects behind it to appear redder than they actually are, which is referred to as interstellar reddening. By comparing spectra of reddened and unreddened objects of a similar type, an extinction or attenuation curve can be determined, showing the amount of extinction a certain amount of dust causes across the electromagnetic spectrum. The difference between the two terms is the relative position of the source and the dust: extinction refers to the situation of dust located in between the source and the observer (mainly galactic stars, but also quasars with a galaxy in front), while attenuation concerns the case where the dust and source(s) are intermixed (mainly extragalactic sources as well as star formation regions). The most obvious feature of the averaged extinction curve for the Milky Way is located at 2175 Å (Figure 1.1), usually attributed to aromatic carbon (i.e. molecules with ring structure), which would also explain the non-linear rise at FUV wavelengths (Weingartner & Draine 2001; Draine 2003a, 2004; Dwek 2005; Draine 2009a; Compiègne 2010; Demyk 2011). Further features in the mid infrared (MIR) are likely associated with stretching and bending modes of C–C or C–H bonds in aliphatic (i.e. in a chain structure) as well as aromatic hydrocarbons, and of Si–O (and O–Si–O in the case of bending modes) within amorphous silicate grains, possibly covered with different types of ices (Pendleton & Allamandola 2002; Draine 2003a, 2004; Dwek 2005; Draine 2009a; Compiègne 2010; Demyk 2011).

Nearly all of the energy absorbed by dust is radiated in the IR or millimetre portion of the electromagnetic spectrum (Figure 1.2). Grains which are considered big and

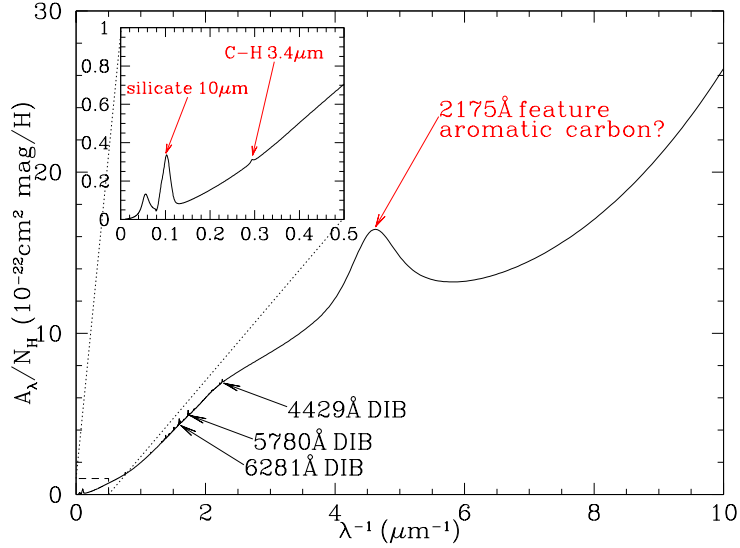


Figure 1.1: Averaged extinction curve for interstellar dust in Galactic diffuse clouds as a function of the wavelength's reciprocal. Some specific features, such as some, as of yet unexplained, diffuse interstellar bands (DIBs), are indicated (Draine 2009a, based on data from Fitzpatrick 1999).

comprise most of the dust mass, do this as a modified black-body (sometimes called grey-body) in the far infrared (FIR), since they reach local thermal equilibrium. Although there is a plethora of possible combinations across the various chemical compositions and dust size distributions, with nearly all contributing to this FIR emission, it is usually fitted very well with a modified black-body spectrum of a single effective temperature T_{eff} and spectral index β modelling the dust emissivity (see e.g. Dupac et al. 2001; Dicker et al. 2009 and nearly all papers based on *Herschel* data, for instance Davies et al. 2010; Baes et al. 2010a; Smith et al. 2010; Grossi et al. 2010; Auld et al. 2013; Davies et al. 2013; Fritz et al. 2012 and Verstaappen et al. 2013).

However, these big grains ($\sim 0.1\text{--}1\ \mu\text{m}$ in size) cannot reach the high temperatures necessary to explain the dust emission in the MIR when they are embedded in an interstellar radiation field (ISRF). On the other hand, a very small grain (below 10 nm in size, down to just a few tens of atoms) has such a tiny heat capacity, that the absorption of even a single UV or optical photon is enough to beat up its temperature to very high levels. These are necessary to account for the MIR emission. This emission is the result of all the photons radiated away by these very small grains to cool down until they reach their fundamental temperature or until the next absorption event. This process is called stochastic heating and is responsible for the overall MIR emission, which is an integrated spectrum over all possible grain sizes and types and, crucially, all attainable temperatures. As long as the average time between absorption events is long enough for the very small grains to cool down to their fundamental temperature

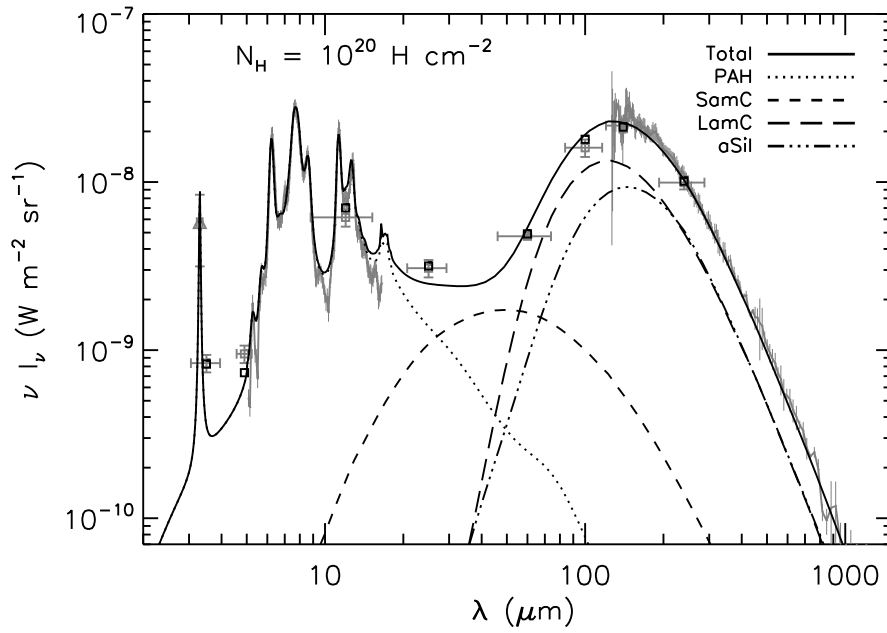


Figure 1.2: Averaged dust spectral energy distribution (SED) in the NIR, MIR and FIR wavelength range for the Diffuse High Galactic Latitude medium, with data shown in grey and with datapoints, and modelled with a combination of PAHs, small (SamC) and large (LamC) amorphous carbonaceous as well as amorphous silicate (aSil) grains (Compiègne et al. 2011).

level, the temperature distribution (and therefore also the total MIR emission) is more dependent on the energy content of the photon in an average absorption event, rather than the overall intensity of the exciting radiation field (Figure 1.3). Consequently, due to its sensitivity to the size of the very small grains through their heat capacity, the overall shape of the MIR emission puts a constraint on the size distribution (Desert et al. 1986; Compiègne 2010; Demyk 2011). As a result, MIR spectroscopy has become an important way to study the dust properties in the ISM of nearby galaxies over the past few years (see e.g. Genzel & Cesarsky 2000; Helou et al. 2000; Smith et al. 2007; Draine et al. 2007).

The near infrared (NIR) and MIR dust emission spectrum also shows a number of strong emission features. These are generally attributed to polycyclic aromatic hydrocarbons (PAHs) (Puget et al. 1985; Puget & Leger 1989; Allamandola et al. 1985, 1989; Draine 2003a, 2004; Dwek 2005; Tielens 2008; Compiègne 2010; Demyk 2011). Although no equivalent PAH has been identified in laboratory studies on Earth, they are now usually called PAH features, because this kind of carbonaceous large molecules are the most likely source for them. These interstellar molecules are thought to carry about a fifth of the total amount of carbon present in the interstellar dust (Tielens 2008; Compiègne 2010; Demyk 2011) and, given their small size, are therefore a major con-

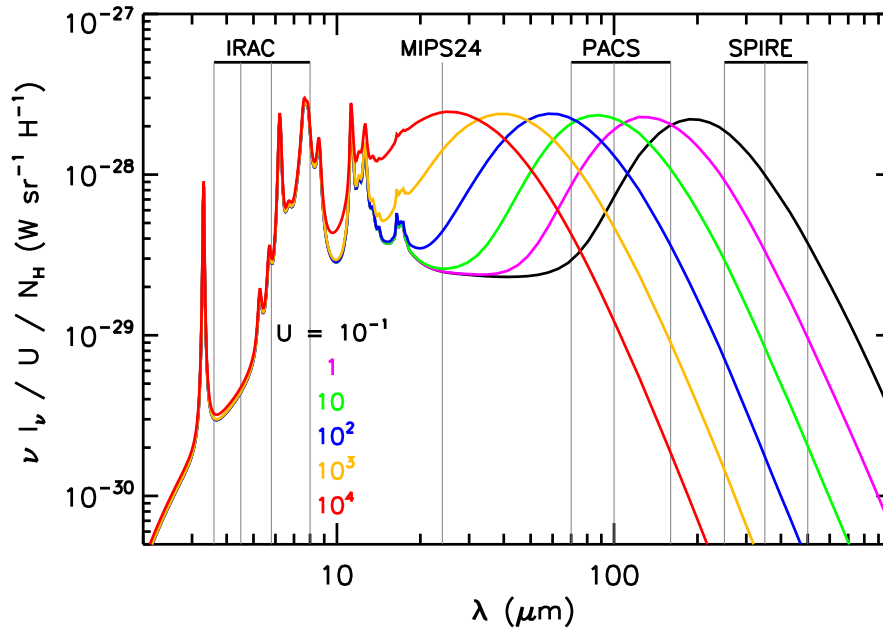


Figure 1.3: modelled SED for dust bathed in a Mathis et al. (1983) radiation field which is multiplied with a scaling factor U , per H atom and divided by U . Various *Spitzer* and *Herschel* instruments are indicated at their photometric wavelengths (Compiègne 2010).

tributor of surface reaction sites. The heating mechanism is similar to the one for very small grains, but their molecular nature causes PAHs to radiate at certain energy levels, with some width due to variations in isotopes or specific structural compositions of the molecules. Because they are so small and therefore also easily destroyed by the radiation field in the more diffuse ISM, PAHs, along with the larger dust grains, are useful as tracers of the ISM conditions (Compiègne 2010; Demyk 2011), e.g. at sites of active star formation (Calzetti et al. 2007; Calzetti et al. 2010; Calzetti 2011, and references therein).

1.2

Radiative transfer modelling

To study the physical and chemical properties of interstellar dust, an important route of enquiry is modelling the effect it has on the light passing through it and thus being absorbed or scattered by it for various possible astronomical objects (Steinacker et al. 2013). This is generally done by defining a spatial distribution of the light source or sources and of the various types of dust, with associated size distributions, throughout the astrophysical system under investigation and then solving the so-called radiative transfer equation (RTE) for this system (Chandrasekhar 1960; Rybicki & Lightman 1979). Described in broad terms, this equation governs the relation between the

amount of energy absorbed from the radiation field within a certain volume of material and the amount added to this field from within this volume, for a specific direction over a wavelength and time interval, using properties of the material such as its density, its opacity and its emissivity.

This equation has source terms and sink terms, adding and removing photons to and from a beam respectively. The sources are usually stellar emission, dust thermal emission and scattering from all other directions into one specific direction, while the sinks are dust absorption and scattering. This equation must then be solved given properties and distributions for the dust and stellar emission under the condition of the energy balance equation, which means that the total energy absorbed from the mean intensity over the entire spectrum must be equal to the amount of energy radiated by the absorbing dust over the entire spectrum. The latter can happen in local thermal equilibrium (LTE), when the dust is at such a temperature that its radiated energy is almost immediately re-absorbed from the radiation field, or not (NLTE), meaning absorption events are sparse in time and dust temperatures can vary rapidly.

Since both stellar and dust components show a three-dimensional distribution in most astrophysical objects, a 3D treatment of the radiative transfer equation is necessary for all but the simplest, symmetrical situations in order to properly study the properties of these systems, and more specifically, the behaviour of the dust within them. However, this is computationally very intensive, because even assuming a steady-state situation, i.e. ignoring any temporal variation, the problem is in essence 6D: 3 spatial dimensions, 2 directional dimensions and 1 wavelength dimension. Moreover, it is both non-local and non-linear: at each location within the system, the radiation field has to be determined for each wavelength and for all directions. The non-locality applies to the spatial, the directional and the wavelength dimensions, since photons can traverse the complete system and can be scattered as well as absorbed and re-emitted in an entirely different direction, while the latter process also changes their wavelength. In the general case, the dust thermal emission behaves in a non-linear manner, being determined by a double-integral equation (Steinacker et al. 2013).

Because of the inherent difficulty of this problem, analytical solutions are impossible for most situations. Instead, an intelligent gridding of the different dimensions is required to minimise the necessary amount of computations (Steinacker et al. 2013), and numerical codes are applied, many of which use the Monte Carlo (MC) approach (e.g. Baes et al. 2003; Baes et al. 2011; Bianchi et al. 1996; Bianchi 2008; Gordon et al. 2001; Misselt et al. 2001; for a more extensive overview of astrophysical MC RT codes, see Steinacker et al. 2013 and Whitney 2011). The latter involves using a random number generator to draw a value from a probability distribution function for various properties which are known to be randomly distributed in realistic systems. In the specific

case of radiative transfer codes, these random numbers govern the behaviour of the radiation transport through a dusty medium by emitting a large but finite number of photons through the system. The random numbers are applied to variables such as the position of light sources, emitting photons in random directions, which are usually distributed isotropically, and to the position and type of interactions (scattering, absorption) of these photons with the dust. In this manner, the amount of energy absorbed by dust at each grid position is sampled and subsequently, these heated dust grains emit photons in their own right, generally at longer wavelengths, again with directions and later interactions determined by sampling from the relevant probability distribution functions using random numbers (Steinacker et al. 2013; Whitney 2011).

The origins of the Monte Carlo method lie in the aftermath of the Manhattan Project, when Stanisław Ulam and John von Neumann were still working at Los Alamos, and came up with the method for the calculation of neutron diffusion, in essence also a radiation transport problem, but it was not until 1949 before the first unclassified paper on the subject was published (Metropolis & Ulam 1949; Metropolis 1987). The first astrophysical dust RT approaches date back just over 40 years (e.g. Mattila 1970; Roark et al. 1974; Witt & Stephens 1974; Witt 1977), and in this time period, it has evolved dramatically with an increase in complexity of many orders of magnitude.

Other methods for solving the radiative transfer equation exist, such as ray tracing, which works in a similar way as the MC radiative transfer, but instead of letting the large number statistics do the hard work, special care is taken to determine which directions are most important to send photon rays along (Steinacker et al. 2013). Still another example of a solving method is the discretisation of the RTE itself using finite differences, leading to a system of linear equations (Stenholm et al. 1991; Steinacker et al. 2002), for which it is however very difficult to find a solution, even with the best matrix solvers (van der Vorst 1992).

Big dust grains absorbing heating photons redistribute the acquired energy among their many internal energy levels according to the Boltzmann distribution, which depends on the dust temperature only. The modified black-body emission originating from this dust temperature cools down the grains again, thereby attaining LTE at an equilibrium temperature when it is in balance with the ambient radiation field. It is then relatively straightforward to calculate the global equilibrium temperature, e.g. from tabulated values, for all big grains of a specific dust species around a particular location, since the radiation field is fixed for that location. However, very small grains (VSGs) do not reach LTE, since the heating events of absorbing photons are much more intermittent and form essentially a stochastic process due to the very small size of these grains, while the cooling happens more continuously. This results in an ensemble of VSGs with a distribution of temperatures, sometimes referred to as NLTE, which is

much more difficult to calculate and in general requires a dedicated treatment. Even though various approaches exist (see e.g. Dwek 1986; Desert et al. 1986; Guhathakurta & Draine 1989; Siebenmorgen et al. 1992; Draine & Li 2001; Compiègne et al. 2011), these solutions come at such a high computational cost that no current 3D radiative transfer code fully incorporates NLTE emission over the entire simulation domain. A more detailed discussion of the radiative transfer equation, focussing on the SKIRT radiative transfer code, will follow in Chapter 2.

1.3

Observing dust in galaxies through infrared astronomy

Infrared radiation from the Sun was discovered by William Herschel in 1800 when he noticed an increase in temperature measured with a thermometer positioned beyond the red part of the spectrum generated with a prism refracting the solar rays (Herschel 1800). Even though the Moon and a few stars were observed in the infrared later on, infrared astronomy did not take off in full until the latter half of the 20th century, when technological improvements in the detectors and the surge of radio astronomy made it clear to the astronomical community that valuable information about various celestial objects could be gathered beyond the visible range of the spectrum.

Because the Earth's atmosphere itself emits in the infrared and contains water vapour which absorbs an important part of the spectrum at infrared wavelengths, infrared astronomy is banished to either outer space, or high altitude and very dry locations, which are above most of the water vapour within the atmosphere. However, since the latter are also ideal places for regular optical astronomy, most large observatories offer specific instrumentation to observe in the infrared windows where the atmosphere is transparent. Space based infrared astronomy kicked off with the launch of the Infrared Astronomical Satellite (IRAS) in 1983 (observing in the wavelength range 12–100 μm , Neugebauer et al. 1984), and continued with specific capabilities of the instruments aboard the Hubble Space Telescope (HST) (IR coverage up to $\sim 1.8 \mu\text{m}$ or $\sim 2.5 \mu\text{m}$ with WFPC3 and NICMOS respectively, MacKenty et al. 1997; Robberto et al. 2000; Cheng et al. 2000; Viana et al. 2009) taken into orbit in 1990 and the *Infrared Space Observatory* (ISO) in 1995 (Kessler et al. 1996, 2.5–240 μm). A whole flurry of observatories were launched in the 2000s, with the *Spitzer Space Telescope* in 2003 (Werner et al. 2004, 3.6–160 μm), Akari in 2006 (Murakami et al. 2007, 2–180 μm), and the *Herschel Space Observatory* (Pilbratt et al. 2010, 55–671 μm) and the Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010, 3.4–22 μm) both in 2009.

A distinction should be made between NIR (roughly 0.65–5 μm) on the one hand, and MIR (~ 5 –25 μm) and FIR (~ 25 –500 μm) on the other hand: the former is primarily

due to stellar emission, while the latter is mainly caused by dust emission. This difference also plays out on an instrumental level: the former can generally be observed using similar technology as CCD (charge-coupled device) cameras, but as the desired wavelength to be observed increases, the necessary band gap becomes too small to use the same working principle as CCDs. Therefore designers of the type of instruments for observations in the latter bands, have to resort to different technologies, such as bolometers for instance. An added difficulty is that these require some kind of cryogenic cooling technique. This problem is usually mitigated with a large reservoir of coolant (mainly liquid He is used), but as this is gradually vapourised over the course of the observing mission until it runs out, the carried amount of coolant puts a hard limit on the lifetime of FIR missions. Some MIR space observatories, such as *Spitzer* and WISE, can continue with a so-called warm mission after the depletion of their coolant supply, but these are restricted to the shortest wavelengths.

An additional problem for FIR astronomy is the diffraction limit: any well-designed space telescope can only resolve distinct sources at least an angular distance $\theta \approx 1.22 \frac{\lambda}{D}$ apart, with λ the wavelength of the observation and D the diameter of the aperture, i.e. the telescope primary mirror size. So as the wavelength to be observed increases, so must the telescope size to achieve the same angular resolution. But this is of course an almost insurmountable task for a space based observatory: its dimensions are inevitably limited by the capacities of the launch system. The *Herschel Space Observatory* is unique in this respect, in that it is the first to cover almost the entire FIR part of the spectrum, and also the first dedicated infrared space based observatory to carry a mirror over 1 metre in size. Its primary mirror with a diameter of 3.5 m is in fact the largest mirror for astronomical purposes in space, and will only be surpassed when the James Webb Space Telescope will be launched, planned for near the end of this decade. The capabilities of *Herschel* in comparison with earlier observatories are demonstrated in Figure 1.4.

Since the FIR and submillimetre part of the spectrum is dominated by the dust emission, and more specifically by the colder dust, it is an excellent waveband to study the different properties and the spatial distribution of the dust, provided the resolution due to the diffraction limit is high enough. The variation of these properties under differing environmental conditions within the ISM and the role of dust in star forming regions form important questions which greatly benefit from spatially resolved investigations of nearby galaxies in this part of the spectrum. Excellent example surveys which have taken advantage of the recent surge in observatories include SINGS (*SIRTf* Nearby Galaxies Survey or *Spitzer* Infrared Nearby Galaxies Survey, Kennicutt et al. 2003), KINGFISH (Key Insights on Nearby Galaxies: A Far-Infrared Survey with *Herschel*, Kennicutt et al. 2011) and HRS (*Herschel* Reference Survey, Boselli et al.

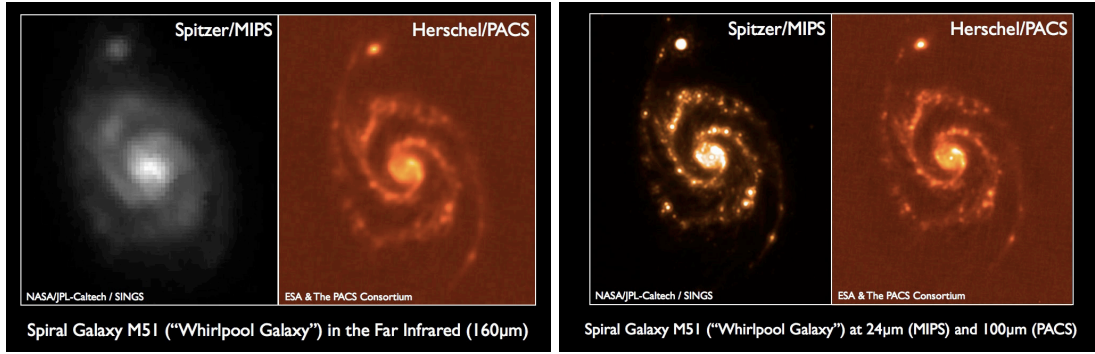


Figure 1.4: A showcase of the advantages a large primary mirror provides due to the diffraction limit, applied to M51 data from *Spitzer* and *Herschel*. *Left:* Observing at the same wavelength, *Herschel* delivers a much higher resolution map than the smaller *Spitzer Space Telescope*. *Right:* At a wavelength about four times longer, *Herschel* sees the galaxy with roughly the same resolution as the four times smaller *Spitzer* does.

2010b), and they provide a benchmark for similar, global observations of galaxies at much higher redshift.

This kind of research in high detail of dust contained in nearby galaxies can provide vital clues for the investigation of star formation, and therefore also of galaxy evolution history. Edge-on spiral galaxies are ideal objects of study in this respect: they have a unique line-of-sight perspective, in which the whole galaxy is projected onto a thin streak of sky area, its surface brightness is therefore increased, and the dust can usually be seen as a prominent central or diffuse dust lane in optical images. This same projection effect makes dust emission and extinction traceable out to large distances from the centre along both the radial and the vertical direction (e.g. Alton et al. 1998b,a; Dupac et al. 2003; Popescu & Tuffs 2003).

The dust distribution and properties in spiral galaxies can be constrained in the strongest manner with a self-consistent treatment of dust extinction and thermal emission, by studying the dust energy balance, which states that the dust must emit the same amount of energy as it absorbs. Within this branch of extragalactic astrophysics, edge-on spirals are once more ideal targets, as their optical images can be fitted to realistic radiative transfer models in order to determine a good estimate of their dust distribution (Kylafis & Bahcall 1987; Xilouris et al. 1997, 1998, 1999; Alton et al. 2004; Bianchi 2007; Baes et al. 2010b; De Looze et al. 2012a). It turns out this dust disc is usually vertically thinner but radially more extended than the stellar disc, and the galaxy should be transparent when seen from above the disc.

However, a comparison of the optical extinction with the FIR/sub-mm emission leads to a discrepancy, since the dust discs of the models absorb only about 10% of the stellar emission, while FIR/sub-mm observations of spiral galaxies point to the dust actually

reprocessing about 30% of the UV and optical radiation (Popescu & Tuffs 2002; Davies et al. 2012). This is exemplified in specific cases of edge-on spirals, where radiative transfer models correctly explain the optical extinction but generally predict FIR/sub-mm flux levels about a factor three lower than the observed values (Popescu et al. 2000a; Misiriotis et al. 2001; Alton et al. 2004; Dasyra et al. 2005; Baes et al. 2010b; De Looze et al. 2012a). This so-called dust energy balance problem needs a solution, and two differing explanations have been proposed: either the dust emissivity in the FIR/sub-mm is significantly underestimated (Alton et al. 2004; Dasyra et al. 2005), or a large fraction of the FIR/sub-mm emission originates from dust with barely any influence on the extinction for the majority of the stellar radiation, such as in dense clumps (Popescu et al. 2000a; Misiriotis et al. 2001; Bianchi 2008). A detailed study of edge-on spirals using both radiative transfer models and FIR/sub-mm observations could shed more light onto this conundrum.

1.4

Overview of this thesis

The following is a general overview of the goals and work carried out during the course of the PhD, which will be described in more detail in the following Chapters of this thesis.

1.4.1 Goals

The overall objective of the thesis is to perform a thorough investigation of the dust content in galaxies and its infrared emission. This requires two main parts: on the one hand, the launch of *Herschel* has started off an exciting era of new, much more resolved and sensitive observations in a largely untouched part of the spectrum, opening up a grand potential for new discoveries. On the other hand, a tool to investigate these new observations, linking together the different ways in which dust is observable (attenuation/extinction in optical/NIR, emission in MIR/FIR) is invaluable. With this thesis, we aim to make significant progress in both areas, by extending the existing SKIRT tool with new capabilities, and by reducing and interpreting *Herschel* data.

Originally, the radiative transfer code SKIRT (Stellar Kinematics Including Radiative Transfer) was developed to investigate the observed kinematics affected by dust scattering and absorption in dusty galaxies, later incorporating the self-consistent calculation of LTE dust emission. Due to the importance of MIR emission to characterise various properties of interstellar dust as well as galaxies from SEDs, a proper treatment of small grains and PAHs, previously lacking, should be included into the code as one of the main goals for this PhD.

As the UGent is responsible for the PACS data reduction (DR) in a number of *Herschel* projects, in some cases as the leading institution, a profound investigation of standard data reduction pipeline and its various input parameters formed another important objective of this PhD. As a consequence, several map-making algorithms and their resulting maps should also be compared to each other. The reason for this is that prior to *Herschel*, FIR astronomy was very much an uncharted territory, and to this day its data reduction still remains more of an art rather than a science.

This investigation should lead to the production of high-quality PACS maps, to be delivered to the various collaborations managing the different observing proposals. These maps should result in excellent, ground-breaking scientific results exploring the FIR part of the spectrum with unprecedented high resolution and sensitivity, putting relatively firm constraints on the dust temperatures and masses and the spatial distributions of these properties.

The final purpose of this PhD is the first stage of an in-depth study which will allow to investigate the distribution, properties and amount of interstellar dust and gas, stars and dark matter within a number of large edge-on spiral galaxies with clear dust lanes. This will take advantage of *Herschel's* excellent capabilities in the FIR, and together with optical data, the results will be combined with radiative transfer modelling in order to get a very complete image of the dust in nearby galaxies, e.g. by researching the dust energy balance problem in a systematic way for several different galaxies.

1.4.2 Outline

An overview of the functionality available within SKIRT is described in Chapter 2, with a special emphasis on the inclusion of NLTE emission by VSGs and PAHs and its mathematical treatment.

In Chapter 3, the *Herschel Space Observatory* is described, and more specifically the PACS instrument it houses. The different steps within the standard pipeline for the PACS photometry data reduction are discussed, as well as 3 different mapping techniques and the modification to this standard pipeline they require. The Chapter concludes with a comparison between these map making methods, both qualitatively and quantitatively. While many of these techniques were provided by the relevant instrument consortia, an investigation of various options, depending on the observed sources and the intended science, was still required.

Two high-profile observing programmes using the *Herschel Space Observatory* are presented in Chapter 4 and Chapter 5 respectively: the *Herschel* Virgo Cluster Survey (HeViCS), targetting the most nearby galaxy cluster in a large area survey, and the

Herschel Exploitation of Local Galaxy Andromeda (HELGA), covering the closest large galaxy beyond the Milky Way, the Andromeda Galaxy or M31, along with its extended sky surroundings. For HeViCS, flux measurements of covered galaxies are compared with literature values, carrying out the photometry in two different ways. Selected results are a FIR view of the central galaxy, M87, in the Virgo Cluster, a resolved dust analysis for 3 spiral galaxies, NGC 4501, NGC 4567 and NGC 4568, and a study of the dust content of 3 FIR detected star-forming dwarf galaxies, all located within the same galaxy cluster, as well as the global FIR morphology within M31.

A dedicated programme, observing a sample of 7 edge-on galaxies with large angular sizes and prominent dust lanes, is discussed in Chapter 6. The *Herschel* Observations of Edge-on Spirals (*HEROES*) aims at studying the amount, spatial distribution and properties of the interstellar dust within these galaxies in detail as well as linking this to the distribution and properties of stars, interstellar gas and dark matter within them. This programme is started off with a description of the FIR morphologies from the *Herschel* data, as well as a first global analysis of this data, determining the dust masses from the FIR fluxes using modified black-body SED fitting and comparing those masses with the values found in the literature, based on the radiative transfer modelling of optical data.

Finally, a summary of the results and an outlook on possible future work is presented in Chapter 7.

Monte Carlo dust radiative transfer including thermal emission from very small grains

2

In this Chapter (largely corresponding to Baes et al. 2011 with some additional material on the NLTE calculations), an updated version of the SKIRT Monte Carlo radiative transfer code is presented. This code, of which the name is an acronym for Stellar Kinematics Including Radiative Transfer, was initially developed to study the effect of dust absorption and scattering on the observed kinematics of dusty galaxies (Baes & Dejonghe 2001a, 2002; Baes et al. 2003). In a second stage, the SKIRT code was extended with a module to self-consistently calculate the dust emission spectrum under the assumption of local thermal equilibrium (Baes et al. 2005a,b). This LTE version of SKIRT has been used to model the dust extinction and emission of various types of galaxies (Gomez et al. 2010; Baes et al. 2010b; De Looze et al. 2010), as well as circumstellar discs (Vidal & Baes 2007) and clumpy tori around active galactic nuclei (Stalevski et al. 2012; Popović et al. 2012). This Chapter discusses a strongly extended version of the SKIRT code that can perform efficient 3D radiative transfer calculations including a self-consistent calculation of the dust temperature distribution and the associated FIR/sub-mm emission with a full incorporation of the emission of transiently heated grains and PAH molecules. First, an introduction to the dust radiative transfer problem is given in Section 2.1 and the radiative transfer equation is discussed in some detail in Section 2.2, followed by a general overview of the SKIRT algorithm (Section 2.3). Some of its specific capabilities are discussed in Section 2.4, while the treatment of dust emission by VSGs and PAHs within SKIRT is described with the mathematical and physical foundations in Section 2.5 and the implementation in Sections 2.6 and 2.7. The updated code is then applied to a gradually refined model of an edge-on galaxy in Section 2.8 and we finish off with some closing remarks on the SKIRT code in its current state in Section 2.9.

The main contribution I delivered to this updated version of SKIRT is situated in the NLTE treatment discussed in Sections 2.5 to 2.7, for which I was personally responsible. I have also made a considerable effort in the streamlining of the code, consolidating the incremental improvements added over the years into the homogenised codebase with consistent function interfaces it has now become, verifying and improving several interfaces, functionality and algorithms in the code. I have also devoted time to the

testing and benchmarking of the code, as part of an ongoing benchmarking effort by several developers of dust radiative transfer codes.

Although the SKIRT code with its new capabilities is not yet used specifically in the observational programmes discussed in later Chapters, it will be used in future research on these observations. This is especially true for the *HEROES* sample targetting edge-on galaxies, which are excellent objects to perform dust radiative transfer studies. It should be mentioned that this new SKIRT version has already found applications in other, related papers, such as De Looze et al. (2012b) and De Looze et al. (2012a), not discussed in detail in this thesis.

2.1

Introduction to dust radiative transfer

The effects of absorption and scattering by interstellar dust grains on the structural parameters of galaxies has been a long-standing and controversial issue. The only way to tackle this problem is to properly solve the continuum radiative transfer equation, taking into account realistic geometries and the physical processes of absorption and multiple anisotropic scattering. Over the years, many different and complementary approaches have been developed to tackle the continuum radiative transfer problem in simple geometries such as spherical or plane-parallel symmetry. While one-dimensional radiative transfer calculations have been crucial to isolate and demonstrate the often counter-intuitive aspects of important parameters such as star-dust geometry, dust scattering properties and clumping (Bruzual et al. 1988; Disney et al. 1989; Witt et al. 1992; di Bartolomeo et al. 1995; Baes & Dejonghe 2001b; Inoue 2005), we need more sophisticated radiative transfer models to model complicated systems such as disc galaxies in detail. Thanks to new techniques and ever increasing computing power, the construction of 2D and 3D realistic radiative transfer models is now possible (e.g. Xilouris et al. 1999; Popescu et al. 2000a; Gordon et al. 2001; Steinacker et al. 2003; Semionov & Vansevičius 2005; Pinte et al. 2006; Jonsson 2006; Bianchi 2008). For an overview of 3D dust radiative transfer codes, see Steinacker et al. (2013).

A complementary and powerful way to study the content of galaxies is to use the direct emission of dust at long wavelengths. Large dust grains will typically reach a state of local thermal equilibrium (LTE) in the local interstellar radiation field (ISRF) and re-radiate the absorbed UV/optical radiation at far-infrared (FIR) and sub-mm wavelengths. Thanks to the spectacular advances in instrumentation in the FIR/sub-mm wavelength region, we have seen a significant improvement in the amount of available data on both nearby and distant galaxies in this part of the spectrum. In particular, the launch of the *Herschel Space Observatory* with the sensitive PACS and

SPIRE instruments has enabled both the detailed study of nearby, resolved galaxies (Bendo et al. 2010a; Galametz et al. 2010; Pohlen et al. 2010; Roussel et al. 2010; Smith et al. 2010) and the detection of thousands of distant galaxies (Clements et al. 2010; Oliver et al. 2010; Rigby et al. 2011). Whereas large grains typically emit as a modified black-body at an equilibrium temperature of 15–30 K and hence dominate the FIR/sub-mm emission of galaxies, small grains and PAH molecules are transiently heated by the absorption of single UV photons to much higher temperatures. The NLTE emission from very small grains and PAHs dominates the emission of galaxies at mid-infrared wavelengths. The *ISO* and particularly the *Spitzer* mission have been instrumental in uncovering the mid-infrared emission of nearby galaxies (Helou et al. 2000; Smith et al. 2007; Draine et al. 2007).

Different approaches have been developed to calculate the NLTE emission spectrum due to very small grains and PAHs (Dwek 1986; Desert et al. 1986; Guhathakurta & Draine 1989; Siebenmorgen et al. 1992; Draine & Li 2001; Compiègne et al. 2011), but the integration of NLTE emission into radiative transfer codes has proven to be a challenging task. The main reason is that the computational effort necessary to calculate the temperature distribution of the different dust grains is substantial. In the general case, the calculation of the dust emissivity in a single dust cell requires the solution of a large matrix equation for each single dust population, with the size of the matrix determined by the number of temperature or enthalpy bins. In the so-called thermal continuous cooling approximation (Draine & Li 2001), this matrix equation can be solved recursively, but still the calculation of the emission spectrum remains a significant computational challenge. Indeed, since the temperature distribution of dust grains depends strongly on both the size of the grains and the strength and hardness of the ISRF, a large number of temperature or enthalpy bins is necessary to sample the temperature distribution correctly. Moreover, because of this strong dependence on grain size and ISRF, the choice of the temperature bins is hard to fix a priori and an iterative procedure is to be preferred.

In spite of the high numerical cost, NLTE dust emission has been built into several radiative transfer codes, using various approximations and/or assumptions. The most simple approach is the one followed by e.g. Wood et al. (2008) and Jonsson et al. (2010), who use a set of predefined NLTE dust emissivities with the simplifying assumption that the emissivity is a function only of strength and not of the spectral shape of the exciting ISRF. A pioneering code in which NLTE dust emission was included in a self-consistent way was the 2D ray-tracing code by Siebenmorgen et al. (1992). The number of temperature distribution calculations are minimised by the assumptions that grains with a size larger than about 80 Å are in thermal equilibrium, and by the use of a pre-fixed time dependence of the cooling of PAH grains. A similar approach was adopted

in the 3D Monte Carlo radiative transfer code DIRTY (Gordon et al. 2001; Misselt et al. 2001). The TRADING code by Bianchi (2008) uses a different approach: this code uses a fixed (and limited) grid of temperature bins for all ISRFs and grain sizes, which allows to precompute and tabulate a significant fraction of the quantities necessary for the calculation of the temperature distribution. Yet a different approach is the work by Juvela & Padoan (2003): driven by the observation that the spectrum of the local ISRF is very similar in many places in a dusty medium, they considered the idea of a dynamic library of dust emission spectra. The idea is that the intensity of the ISRF at a very limited number of reference wavelengths (they typically used only two) suffices to make a reliable estimate of the total ISRF and hence of the dust emission spectrum.

2.2

The 3D continuum radiative transfer equation

The specific intensity of the radiation field $I_\lambda(\mathbf{x}, \mathbf{k})$ in the stationary situation is defined as the amount of energy transported through photon radiation at a position $\mathbf{x}$ in space in the direction of the unit vector $\mathbf{k}$, per wavelength unit interval around its wavelength λ , per unit of solid angle and per unit of time, crossing a unit of area perpendicular to $\mathbf{k}$. The variations of this specific intensity due to an interacting medium with sources and sinks are then described by the continuum radiative transfer equation, which has the general form (see e.g. Chandrasekhar 1960; Rybicki & Lightman 1979; Steinacker et al. 2013):

$$\mathbf{k} \cdot \nabla I_\lambda(\mathbf{x}, \mathbf{k}) = j_\lambda(\mathbf{x}, \mathbf{k}) - \kappa_\lambda(\mathbf{x})\rho(\mathbf{x})I_\lambda(\mathbf{x}, \mathbf{k}) \quad (2.1)$$

In it, the specific intensity change over an infinitesimal path length determined by the position $\mathbf{x}$ and the propagation direction $\mathbf{k}$ is equated to the summed contribution from the source and sink terms, given by the first and second term on the right-hand side, respectively. The source term denotes the added luminosity emitted at the position $\mathbf{x}$ in the direction $\mathbf{k}$, while the sink term is proportional to both the specific intensity and the mass density of the medium, with the mass extinction coefficient $\kappa_\lambda(\mathbf{x})$ as the proportionality constant. The specific intensity could also be expressed in terms of frequency ν instead of wavelength λ , using the equivalence $\lambda I_\lambda = \nu I_\nu$ and $\lambda \nu = c$, but here the wavelength convention will be used.

The radiative transfer equation (2.1) can be transformed into one using s as a one-dimensional variable parametrising the distance along the path determined by the position $\mathbf{x}$ and the direction $\mathbf{k}$:

$$\frac{dI_\lambda}{ds}(s) = j_\lambda(s) - \kappa_\lambda(s)\rho(s)I_\lambda(s) \quad (2.2)$$

Defining the optical depth between two positions s_1 and s_2 as

$$\tau_\lambda(s_1, s_2) = \int_{s_1}^{s_2} \kappa_\lambda(s) \rho(s) ds, \quad (2.3)$$

this differential equation has a formal solution:

$$I_\lambda(s) = \int_{-\infty}^s j_\lambda(s') e^{-\tau_\lambda(s', s)} ds' \quad (2.4)$$

Since the emissivity j usually depends on the specific intensity as well, this is implicitly nothing more than an integral equation form of the radiative transfer equation and as such, it is thus not practically useful to calculate a solution.

It should be noted that equation (2.1) has an even more general form, with the left-hand side replaced by $\frac{1}{c} \frac{\partial I_\lambda(\mathbf{x}, \mathbf{k}, t)}{\partial t} + \mathbf{k} \cdot \nabla I_\lambda(\mathbf{x}, \mathbf{k}, t)$ (with c the speed of light) and with the other quantities on the right-hand side also explicitly depending on the time dimension. However, this temporal version of the continuum radiative transfer would needlessly complicate an already complex situation, since the photon transport usually happens on much shorter time scales than the dynamics of the investigated systems. Notable exceptions are relativistic systems and the energy transport within stars from the core up to the surface, but these require a different approach and are not further discussed here.

The radiative transfer equation for a dusty medium can be constructed from equation (2.1) or (2.2) by incorporating the different physical processes and interactions involved. First considering only absorption and the primary emission $j_\lambda^*(\mathbf{x}, \mathbf{k})$, which is usually stellar emission, but can also include for instance an active galactic nucleus (AGN), the radiative transfer equation becomes:

$$\frac{dI_\lambda}{ds}(\mathbf{x}, \mathbf{k}) = j_\lambda^*(\mathbf{x}, \mathbf{k}) - \kappa_{\lambda, \text{abs}}(\mathbf{x}) \rho(\mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}) \quad (2.5)$$

In this equation, the absorption process, in which part of the electromagnetic radiation is removed from the radiation field by dust grains and converted into their internal energy, is characterised by the absorption coefficient κ_{abs} . In principal, the latter can be determined for a dust grain with a particular size, shape and chemical composition at any wavelength (see e.g. Mie 1908; Purcell & Pennypacker 1973; Draine 1988; Min et al. 2005)

The addition of scattering renders the radiative transfer equation more complicated, since it requires an extra sink and source term, as it removes radiation from a direction $\mathbf{k}'$ and diverts it into a new direction $\mathbf{k}$. The probability of scattering between these two directions at the position $\mathbf{x}$ is given by the scattering phase function $\Phi_\lambda(\mathbf{k}, \mathbf{k}', \mathbf{x})$,

with the normalisation $\int_{4\pi} \Phi_\lambda(\mathbf{k}, \mathbf{k}', \mathbf{x}) d\Omega' = \int_{4\pi} \Phi_\lambda(\mathbf{k}, \mathbf{k}', \mathbf{x}) d\Omega = 1$. Defining the extinction coefficient $\kappa_{\text{ext}} = \kappa_{\text{abs}} + \kappa_{\text{sca}}$ as the sum of the absorption and scattering coefficients, the radiative transfer equation now couples the radiation field in all positions and directions:

$$\begin{aligned} \frac{dI_\lambda}{ds}(\mathbf{x}, \mathbf{k}) = & j_\lambda^*(\mathbf{x}, \mathbf{k}) + \kappa_{\lambda, \text{sca}}(\mathbf{x})\rho(\mathbf{x}) \int_{4\pi} \Phi_\lambda(\mathbf{k}, \mathbf{k}', \mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}') d\Omega' \\ & - \kappa_{\lambda, \text{ext}}(\mathbf{x})\rho(\mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}) \end{aligned} \quad (2.6)$$

Since any realistic medium likely contains a multitude of dust species, each with differing size, shape, chemical composition and number density, this equation should be modified to incorporate the fraction $w_i(\mathbf{x})$ each of these species i contributes towards the total dust number density, using their own absorption and scattering coefficients and scattering phase functions:

$$\begin{aligned} \frac{dI_\lambda}{ds}(\mathbf{x}, \mathbf{k}) = & j_\lambda^*(\mathbf{x}, \mathbf{k}) + \sum_i w_i(\mathbf{x}) \kappa_{\lambda, \text{sca}, i}(\mathbf{x})\rho(\mathbf{x}) \int_{4\pi} \Phi_{\lambda, i}(\mathbf{k}, \mathbf{k}', \mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}') d\Omega' \\ & - \sum_i w_i(\mathbf{x}) \kappa_{\lambda, \text{ext}, i}(\mathbf{x})\rho(\mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}) \end{aligned} \quad (2.7)$$

However, using appropriate definitions for absorption, scattering and extinction coefficients and scattering phase functions, equation (2.7) can easily be transformed back into equation (2.6) for an averaged dust grain type, if only primary emission, absorption and scattering are considered (Martin 1978; Wolf 2003a).

An often used scattering phase function is the Henyey-Greenstein phase function, which only depends on the scattering angle α between both directions, using $\mathbf{k} \cdot \mathbf{k}' = \cos \alpha$, and an anisotropy parameter defined as $g_\lambda = \int_{4\pi} \Phi_\lambda(\cos \alpha) \cos \alpha d\Omega'$ (Henyey & Greenstein 1941):

$$\Phi_\lambda(\cos \alpha) = \frac{1}{4\pi} \frac{1 - g_\lambda^2}{(1 + g_\lambda^2 - 2g_\lambda \cos \alpha)^{\frac{3}{2}}} \quad (2.8)$$

Even though this phase function was only defined empirically for light scattering in Galactic reflection nebulae and has no physical foundation, it proves widely applicable with remarkable accuracy.

When the dust emission is taken into account as well, an additional source term $j_{\lambda, \text{d}}(\mathbf{x})$ must be included:

$$\begin{aligned} \frac{dI_\lambda}{ds}(\mathbf{x}, \mathbf{k}) = & j_\lambda^*(\mathbf{x}, \mathbf{k}) + j_{\lambda, \text{d}}(\mathbf{x}) + \kappa_{\lambda, \text{sca}}(\mathbf{x})\rho(\mathbf{x}) \int_{4\pi} \Phi_\lambda(\mathbf{k}, \mathbf{k}', \mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}') d\Omega' \\ & - \kappa_{\lambda, \text{ext}}(\mathbf{x})\rho(\mathbf{x}) I_\lambda(\mathbf{x}, \mathbf{k}) \end{aligned} \quad (2.9)$$

Although this seems like a simple extra term, in most cases it is actually critically dependent on the radiation field's intensity in a non-linear manner. Under the assumption that all dust grain species reach LTE with $T_i(\mathbf{x})$ as equilibrium temperature, it can be written as the cumulation of the emission by the different modified black-bodies $B_\lambda(T)$:

$$j_{\lambda,d}(\mathbf{x}) = \sum_i w_i(\mathbf{x}) \kappa_{\lambda,abs,i}(\mathbf{x}) \rho(\mathbf{x}) B_\lambda(T_i(\mathbf{x})) \quad (2.10)$$

However, given the assumption of LTE, all of these dust species must be in balance between the absorbed and re-emitted energy, and so, defining the mean intensity of the radiation field as $J_\lambda(\mathbf{x}) = \frac{1}{4\pi} \int_{4\pi} I_\lambda(\mathbf{x}, \mathbf{k}) d\Omega$, they must each satisfy:

$$\int_0^\infty \kappa_{\lambda,abs,i} J_\lambda(\mathbf{x}) d\lambda = \int_0^\infty \kappa_{\lambda,abs,i} B_\lambda(T_i(\mathbf{x})) d\lambda \quad (2.11)$$

Since very small dust grains do not attain LTE, they actually form a distribution of different temperatures for the same dust species $P_i(T, \mathbf{x})$, and the single factor $B_\lambda(T_i(\mathbf{x}))$ representing a modified black-body in equations (2.10) and (2.11) should actually be replaced by its expected value $\int_0^\infty P_i(T, \mathbf{x}) B_\lambda(T) dT$. A more extensive description of the dust emission, including very small grains, and how to calculate its contribution, will be given further on in this Chapter.

2.3

Overview of SKIRT

2.3.1 Monte Carlo radiative transfer

SKIRT is a 3D continuum radiative transfer code based on the Monte Carlo algorithm. The key principle in Monte Carlo radiative transfer simulations is that the radiation field is treated as a flow of a finite but very large number of photon packages. A simulation consists of consecutively following the individual path of each single photon package through the dusty medium. The journey or lifetime of a single photon package can be thought of as a loop: at each moment in the simulation, a photon package is characterised by a number of properties, which are generally updated when the photon package moves to a different stage on its trajectory. The trajectory of the photon package is governed by various events such as emission, absorption and scattering events. Each of these events is determined statistically by random numbers, generated from the appropriate probability distribution $p(x) dx$. Typically, a photon is emitted by a star, undergoes a number of scattering events and its journey ultimately ends when it is either absorbed by the dust or it leaves the system. A Monte Carlo simulation repeats this same loop for every single one of the photon packages and analyses the

results afterwards.

The mathematical details and practical implementation of Monte Carlo radiative transfer have both been described in detail by various authors (e.g. Cashwell & Everett 1959; Mattila 1970; Witt 1977; Fischer et al. 1994; Bianchi et al. 1996; Gordon et al. 2001; Nicolini et al. 2003; Wolf 2003b; Stamatellos & Whitworth 2003; Juvela 2005; Jonsson 2006; Bianchi 2008; Whitney 2011; Steinacker et al. 2013) and will not be repeated here in full detail. The overall approach is comparable to the DIRTY (Gordon et al. 2001; Misselt et al. 2001) and TRADING (Bianchi 2008) radiative transfer codes and the interested reader is referred to these papers for more details. Only a compact description of the general characteristics of the SKIRT Monte Carlo code will be given and not all the details will be described. Instead, attention will be focused to those aspects of the SKIRT code that are novel and/or different compared to the other codes, with a specific treatment of the emission by very small dust grains, as this forms one of the main subjects of the PhD for which this thesis is the written sublimation.

2.3.2 General overview of a SKIRT simulation

Each SKIRT simulation consists of four phases: the initialisation phase, the stellar emission phase, the dust emission phase, and the clean-up phase.

The initialisation phase

The initialisation phase consists of adopting the correct unit system, setting up the random number generator, computing the optical properties of the various dust populations, constructing the dust grid, setting up the stellar geometry and setting up the instruments of the various observers. Once this initialisation is finished, the actual simulation can start.

The stellar emission phase

In the stellar emission phase, the transfer starting from the primary source of radiation (usually stellar sources, but it can also include an accretion disc or nebular line emission) through the dusty medium is considered. The stellar emission phase consists of a set of parallel loops, each of them corresponding to a single wavelength. At every single wavelength, the total luminosity of the stellar system is divided into a very large number (typically 10^5 to 10^7) of monochromatic photon packages, which are launched consecutively through the dusty medium in random propagation directions.

Once a photon package is launched into the dusty medium (either after an emission event or following a scattering event), it can be absorbed by a dust grain, it can be scattered by a dust grain, or it can travel through the system without any interaction. In a naive Monte Carlo routine, these three possibilities are possible and it is randomly determined which of the three will happen, according to their respective probabilities. This is generally an inefficient procedure, though, which leads to poor signal-to-noise both in the absorption rates in the different cells and in the scattered light images. A combination of continuous absorption and eternal forced scattering (see Section 2.4.3 for details) have been set up to overcome these problems. The result is that, contrary to most Monte Carlo codes where the life cycle of a photon package ends when it either leaves the system or is absorbed, the photon packages in SKIRT can never leave the system. The life cycle of a photon package ends when the package contains virtually no more luminosity (typically the used criterion is that it must have lost 99.99% of its original luminosity). Whenever this happens, a different stellar photon package is launched until this one finishes its life cycle as well. This loop is repeated for all stellar photon packages at a given wavelength, and subsequently for all wavelengths (in a multi-core system, each core can handle the loop corresponding to a different wavelength at the same time).

The dust emission phase

After the stellar emission phase, the code moves to the dust emission phase. This phase is roughly similar to the stellar phase, except that this time, the sources that emit the radiation are not the primary, stellar sources but rather the dust cells. From the stellar emission phase, the total amount of absorbed radiation at each wavelength in each cell of the dust domain is known. From this absorption rate, the mean intensity of the ISRF can be calculated in each cell, which allows the calculation of the dust emissivity, depending on the physical processes the SKIRT user is interested in (see Section 2.4.5). With the sources (the dust cells) and their emissivity determined, the simulation now enters a loop that is very similar to the one in the stellar emission phase. At each individual wavelength, a huge number of photon packages are generated which are then launched and followed consecutively through the dusty medium. Care is taken that all regions of the dusty medium, including those cells where only a small amount of luminosity has been absorbed, are well-sampled.

The dust-emitted photon packages in turn increase the absorption rate in the dust cells where they pass through. This leads to an increase of the mean intensity of the ISRF. The result is that at the end of the dust emission phase, the absorption rates used to calculate the dust emissivity in each cell do not correspond to the mean intensity of the

ISRF. This naturally leads to an iterative procedure, in which the absorption rate, the mean intensity and the dust emissivity are updated until convergence is achieved (Misselt et al. 2001; Bianchi 2008). Hence the dust emission phase of the code is repeated several times. Typically a 1% level accuracy in the dust bolometric absorption rate of each cell is required as a stopping criterion for the iteration. It is typically reached in only a few iterations; for all the simulations done so far, less than five iterations have been necessary.

The clean-up phase

The last phase of the Monte Carlo simulation starts when the last of the photon packages emitted by the dust component has lost 99.99% of its initial luminosity. It simply consists of calibrating and reading out the instruments (all output is written to FITS files) and other useful information, such as 3D absorption rate maps and dust temperature distributions.

2.4

Particular aspects of the SKIRT code

2.4.1 Setup of the dust grid

A critical aspect in Monte Carlo radiative transfer simulations is the choice of the dust grid. The dust grid consists of mostly tiny cells, each of which have a number of characteristics that fully describe the physical properties of the dust at the location of the cell. The choice of the grid has a significant impact on both the run time and the memory requirement of the simulation. Indeed, each photon package typically requires several integrations through the dust (i.e. the determination of the optical depth along the path and the conversion of a given optical depth to a physical path length), and the calculation time of a single optical depth typically scales with the number of grid cells crossed. Different kinds of dust grids can be applied in the SKIRT code. The most general grid is a 3D cartesian grid in which each dust cell is a rectangular cuboid. For simulations with a spherical or axial symmetry, 1D spherical and 2D cylindrical grids are also provided (the elementary dust cells being shells or tori respectively). The distribution of the grid points (in 1D spherical, 2D cylindrical or 3D cartesian grids) can be chosen arbitrarily; linear, logarithmic, or power-law cell distributions have been pre-programmed, but any user-supplied grid cell distribution is possible. A very recent addition is the incorporation of hierarchical 3D grids, in particular octrees and k -d trees (Saftly et al. 2013, submitted; Saftly et al., in preparation). The former divides each cuboid dust cell into 8 smaller cells, either at the midpoint (regular subdivision),

or at the barycentre (barycentric subdivision), until a dust mass criterium is met. The latter subdivides a cell only in two, by means of a plane through the midpoint or the barycentre, but each division happens parallel to a different axis than the one at the tree node above.

The main goal of the dust grid is to discretise the dust density. It is assumed that the density of each dust component is uniform within each individual cell. In principle, the density does not need to be constant within each dust cell (see e.g. Niccolini et al. 2003). The first versions of SKIRT experimented with a more sophisticated kind of dust grid, where the density of the dust within each cell is not uniform but determined by trilinear interpolation of the values of the density on the eight border points of the cell (in case of a cartesian grid with cubic cells). In this case, the computation of optical depths in the dusty medium takes more computation time, but the accuracy is increased such that a simulation requires a grid with less cells and less photon packages. For models in which only absorption and scattering are taken into account, it is found that this kind of dust grid is computationally more efficient than a dust grid with uniform densities within cells, in particular when the system harbors a large dynamical range of dust densities (Baes et al. 2003). However, for radiative transfer simulations in which the thermal emission of the dust is taken into account, each dust cell needs to contain an absorption rate counter, which collects the absorbed luminosity at every wavelength. The size of the dust cells is hence the typical resolution of the simulation, and the advantage of the interpolated grid (where the dust grid can be coarser because the density is resolved within each cell) largely disappears. SKIRT therefore only uses dust grids with a uniform density in each cell.

2.4.2 Sampling the stellar density

The first step in the life cycle of each stellar photon is the random generation of the location where it is emitted. This means that random positions have to be generated from the three-dimensional probability distribution

$$p(\mathbf{x}) \, d\mathbf{x} = \frac{j_{\lambda}^*(\mathbf{x}) \, d\mathbf{x}}{\int j_{\lambda}^*(\mathbf{x}') \, d\mathbf{x}'} \quad (2.12)$$

where $j_{\lambda}^*(\mathbf{x})$ is the luminosity density at the wavelength λ of the photon package, and we assume its emission is isotropic. As SKIRT is primarily focused towards modelling galaxies, efforts have not been spared to optimise the generation of random positions from arbitrary 3D probability functions. The SKIRT code contains a library with common geometries for which the generation of a random position vector can be performed analytically. These include spherical Plummer (1911), Jaffe (1983) or Hern-

quist (1990) models, or axisymmetric power-law, exponential, sech or isothermal disc models. For other frequently used luminosity density profiles, e.g. flattened de Vaucouleurs (1948) or Sersic (1968) models, or more general density profiles that cannot be described by an analytical function, such a direct analytical inversion is not possible. Two complementary approaches have been included in the SKIRT code to deal with generating random positions from such density profiles.

Multi-gaussian expansion technique

The first technique is to expand the density profile into a set of subcomponents. SKIRT contains a routine to perform a multi-gaussian expansion (MGE) of surface brightness distributions. An MGE expansion basically expands any surface brightness distribution as a finite sum of two-dimensional gaussian components (Monnet et al. 1992; Emsellem et al. 1994a; Cappellari 2002). The MGE method has proven to be a very powerful tool for image analysis: even with a relatively modest set of gaussian components, $N \sim 10$, even complex geometries can be reproduced accurately (Emsellem et al. 1994b, 1999; Cappellari 2002; Cappellari et al. 2006; van den Bosch et al. 2008). One of the reasons why a MGE expansion is very useful for SKIRT is that this approach enables a straightforward determination of the 3D spatial distribution: if the Euler angles of the line of sight are known, the de-projection of a 2D gaussian distribution on the plane of the sky is a 3D gaussian distribution and the conversion formulae are completely analytical (Monnet et al. 1992). Generating random positions from a sum of 3D gaussian probability distributions is straightforward. An example of this approach can be seen in Figure 2.1, where we present a radiative transfer model for the Sombrero Galaxy based on the MGE expansion of its surface brightness distribution presented by Emsellem (1995).

The stellar foam

The second approach consists of sampling random positions directly from the stellar density distribution using the so-called stellar foam. The stellar foam is a SKIRT structure based on the Foam library developed by Jadach (2003) and Jadach & Sawicki (2007). Foam is a self-adapting cellular Monte Carlo tool aimed at Monte Carlo integration of multi-dimensional functions, including integrands with an arbitrary pattern of singularities. It achieves a high efficiency thanks to an intelligent division of the integration space into small simplicial or hyper-rectangular form, which are created in a self-adaptive way by binary splitting. It has originally been developed for use in high-energy physics (e.g. Jadach & Skrzypek 2006; Andonov et al. 2010; Haas &

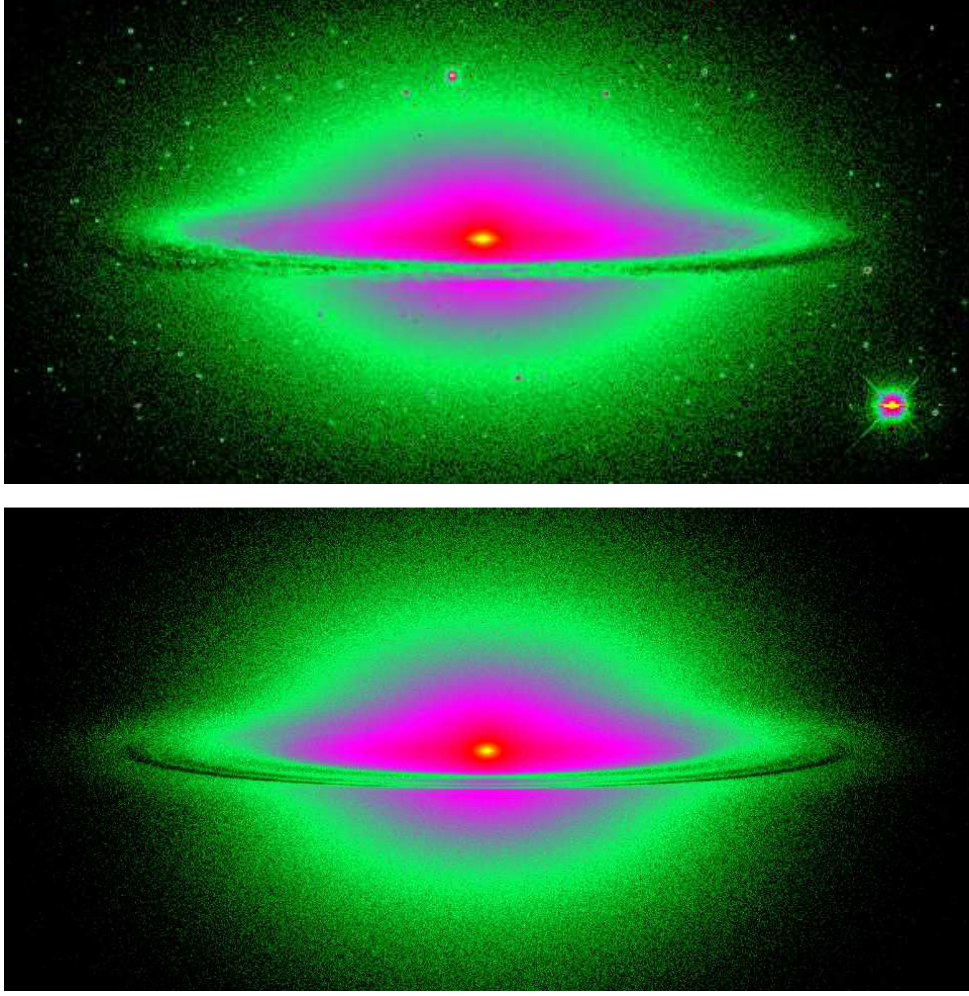


Figure 2.1: Observed (*top*) and simulated (*bottom*) V-band images of the Sombrero Galaxy (M104). The observed image is taken from the *Spitzer* Infrared Nearby Galaxies Survey (SINGS, Kennicutt et al. 2003) ancillary data website. In the SKIRT simulation, the stellar density profile is based on a multi-gaussian expansion (MGE) with 15 components, as presented by Emsellem (1995). For a full-scale panchromatic radiative transfer modelling of stars and dust in M104, see De Looze et al. (2012b).

Makarenko 2011), but it can also be adopted as a general-purpose Monte Carlo event generator.

We use an adapted version of the Foam library for the generation of random positions from an arbitrary probability density $p(\mathbf{x}) d\mathbf{x}$. One problem is that the probability density $p(\mathbf{x}) d\mathbf{x}$ from which we want to generate random positions is typically defined on the entire 3D space, whereas Foam requires a probability density on the N -dimensional unit hypercube $[0, 1]^N$. We achieve this through a coordinate transformation from the usual coordinates $\mathbf{x} = (x, y, z)$ to new coordinates $\tilde{\mathbf{x}} = (\tilde{x}, \tilde{y}, \tilde{z})$ such that we map each infinite interval $[-\infty, \infty]$ onto the unit interval $[0, 1]$. The probability density $p(\mathbf{x}) d\mathbf{x}$,

normalised such that

$$\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} p(x, y, z) dz = 1 \quad (2.13)$$

is transformed to a new probability density

$$\bar{p}(\bar{x}) d\bar{x} = p\left(x(\bar{x}), y(\bar{y}), z(\bar{z})\right) \left| \frac{dx}{d\bar{x}} \frac{dy}{d\bar{y}} \frac{dz}{d\bar{z}} \right| d\bar{x} \quad (2.14)$$

This new density will be defined and normalised to one on the unit cube,

$$\int_0^1 d\bar{x} \int_0^1 d\bar{y} \int_0^1 \bar{p}(\bar{x}, \bar{y}, \bar{z}) d\bar{z} = 1 \quad (2.15)$$

There are many possible transformations we can apply to achieve this. We have chosen the transformation

$$\bar{x} = \frac{1}{\pi} \arctan\left(\frac{a}{x}\right) \quad (2.16a)$$

$$\bar{y} = \frac{1}{\pi} \arctan\left(\frac{b}{y}\right) \quad (2.16b)$$

$$\bar{z} = \frac{1}{\pi} \arctan\left(\frac{c}{z}\right) \quad (2.16c)$$

with a , b and c three scale parameters, which we can adapt for the specific probability density we are considering. The inverse transformation is

$$x = \frac{a}{\tan(\bar{x}\pi)} \quad (2.17a)$$

$$y = \frac{b}{\tan(\bar{y}\pi)} \quad (2.17b)$$

$$z = \frac{c}{\tan(\bar{z}\pi)} \quad (2.17c)$$

and the Jacobian reads

$$\left| \frac{\partial(x, y, z)}{\partial(\bar{x}, \bar{y}, \bar{z})} \right| = \left| \frac{dx}{d\bar{x}} \frac{dy}{d\bar{y}} \frac{dz}{d\bar{z}} \right| = \frac{abc \pi^3}{\sin^2(\bar{x}\pi) \sin^2(\bar{y}\pi) \sin^2(\bar{z}\pi)} \quad (2.18)$$

Summarising, if we want to generate random positions x from an arbitrary probability density $p(x) dx$, we first determine representative scalelengths a , b and c along the three dimensions, and subsequently calculate the corresponding probability density $\bar{p}(\bar{x}) d\bar{x}$ using equations (2.14), (2.17) and (2.18). The foam generator is applied to this new probability function to generate the random points $\bar{x}$, which are converted

to the desired positions $\mathbf{x}$ through the formulae (2.17). The construction of the stellar foam takes only a few seconds in two dimensions up to about one minute in three dimensions.

2.4.3 Eternal forced scattering and continuous absorption

Once a photon package has been generated at a random location (sampled from the stellar density) and it has been given a random propagation direction (sampled randomly from the unit sphere), it is ready to start its journey through the dusty medium. It has three possible fates: it can be absorbed by a dust grain at a certain position along its path, it can be scattered by a dust grain at a certain position on its path, or it can travel along its path through the system without any interaction. The probability for each of these three options are determined by the scattering albedo ω_λ and the optical depth $\tau_{\lambda,\text{path}}$ along the path, defined as

$$\tau_{\lambda,\text{path}} = \int_0^\infty \kappa_\lambda \rho(s) ds \quad (2.19)$$

where κ_λ is the extinction coefficient, ρ is the dust density and the integral covers the entire path of the photon package through the dusty medium. The most straightforward way to model these different physical processes in a Monte Carlo radiative transfer code is to generate randomly which of these three processes will take place. In case the photon package leaves the system, its lifetime is terminated and a different package is launched. In the case of a scattering event, the position of the scattering event is determined by choosing a random path length from the appropriate probability distribution and a scattering event is simulated. Finally, in case it is absorbed, the position of the absorption is determined in a similar way, the luminosity of the photon package is stored in a local absorption rate counter attached to the dust cell where the absorption event took place, and the photon package's life is terminated. These local absorption rates are used in a later stage of the simulation to estimate the local mean intensity of the ISRF, necessary to calculate the thermal dust emission.

This traditional method has two significant drawbacks: along paths where the optical depth is modest, many photon packages will escape from the system without interactions, which will result in bad statistics of the scattered intensity and the absorbed luminosity. Even if the photon packages do interact, most interactions will take place on those sections of the path where the density is largest. Many absorption events are necessary in each cell to guarantee a high-quality estimate of the local absorption rate and the corresponding mean intensity. In dust cells with a low density (such that only few absorptions take place) and at wavelengths where the absorption rate is low, this

usually requires large numbers of photon packages.

These two problems can be minimised using the efficient combination of two clever Monte Carlo techniques: forced scattering and continuous absorption. Continuous absorption (or Lucy estimation) is a technique to estimate the mean intensity of the ISRF throughout the dusty medium (Lucy 1999; Niccolini et al. 2003). The continuous absorption technique is designed to solve the problem of poor statistics in the absorption rate in low-density regions by spreading the absorption over all cells along the photon package's path instead of concentrating it in one single cell. A different but equivalent way to see it is that the mean intensity in each cell is estimated using the sum of the path lengths covered by all photon packages that traverse that particular cell. Forced scattering is an old technique that was already implemented in the first Monte Carlo radiative transfer codes (Cashwell & Everett 1959; Mattila 1970; Witt 1977). When applying forced scattering, photon packages are forced to interact with a dust grain before they leave the system. This incorrect behavior is corrected for by decreasing the luminosity of the photon package.

In most radiative transfer codes, forced scattering is considered only after an emission event and subsequent scattering events are unforced. In the SKIRT code we always consider forced scattering, such that we have eternal forced scattering. The combination of eternal forced scattering and continuous absorption results in a very efficient Monte Carlo routine. Instead of determining randomly whether a photon package with luminosity L_λ will escape, will be absorbed or will be scattered, we split it into $n + 2$ child photon packages (with n the number of dust cells along the path): one child photon package that will leave the system without interaction, one child photon package that will be scattered by a dust grain somewhere along the path, and n children that will be absorbed, one in each of the n cells along the path. The luminosity of each of these children is easy to calculate: we find

$$L_{\lambda, \text{abs}_1} = L_\lambda (1 - \omega_\lambda) (1 - e^{-\tau_{\lambda,1}}) \quad (2.20)$$

$$L_{\lambda, \text{abs}_2} = L_\lambda (1 - \omega_\lambda) (e^{-\tau_{\lambda,1}} - e^{-\tau_{\lambda,2}}) \quad (2.21)$$

$\vdots$

$$L_{\lambda, \text{abs}_{n-1}} = L_\lambda (1 - \omega_\lambda) (e^{-\tau_{\lambda,n-2}} - e^{-\tau_{\lambda,n-1}}) \quad (2.22)$$

$$L_{\lambda, \text{abs}_n} = L_\lambda (1 - \omega_\lambda) (e^{-\tau_{\lambda,n-1}} - e^{-\tau_{\lambda, \text{path}}}) \quad (2.23)$$

$$L_{\lambda, \text{sca}} = L_\lambda \omega_\lambda (1 - e^{-\tau_{\lambda, \text{path}}}) \quad (2.24)$$

$$L_{\lambda, \text{esc}} = L_\lambda e^{-\tau_{\lambda, \text{path}}} \quad (2.25)$$

with $\tau_{\lambda,j}$ the optical depth to the point on the path where the photon package would

leave the j 'th dust cell. Obviously, we have

$$L_{\lambda,\text{esc}} + L_{\lambda,\text{sca}} + \sum_{j=1}^m L_{\lambda,\text{abs}_j} = 1 \quad (2.26)$$

In our Monte Carlo simulation, we now consider each of these $n + 2$ child photon packages. Each one of the n children with luminosity L_{λ,abs_j} is absorbed in the j 'th cell along the path, which means that its luminosity is added to the absorption rate counter attached to this dust cell. The child photon package with luminosity $L_{\lambda,\text{esc}}$ escapes from the system, which implies that we don't have to take this one into account anymore. Finally, the child photon package with luminosity $L_{\lambda,\text{sca}}$ is scattered somewhere along the path. This is basically the only photon package that we need to follow up. We still have to randomly determine the location of the scattering event along the path. This is achieved by selecting a random optical depth τ_λ from an exponential distribution over the finite range $0 < \tau_\lambda < \tau_{\lambda,\text{path}}$, i.e.

$$p(\tau_\lambda) d\tau_\lambda = \frac{e^{-\tau_\lambda} d\tau_\lambda}{1 - e^{-\tau_{\lambda,\text{path}}}} \quad (2.27)$$

and translate this randomly generated τ_λ to a physical path length by solving the equation

$$\tau_\lambda = \int_0^s \kappa_\lambda \rho(s') ds' \quad (2.28)$$

for s . Once this path length has been determined, we can determine the position of the scattering event. If we then also determine a new propagation direction, determined randomly by generating a random direction from the scattering phase function, we are back at the starting point. This child now becomes the parent, it can be split into children and we can repeat the same loop all over again.

Summarising, the net result of the combination of continuous absorption and eternal forced scattering is that after each emission/scattering event, we distribute a fraction of the photon package's luminosity among all the cells along the path, and we continue the Monte Carlo loop with a less luminous photon package that is always scattered at some point along the path. Hence, contrary to most Monte Carlo codes where the life cycle of a photon package ends when it either leaves the system or is absorbed, the photon packages in SKIRT can never leave the system. The life cycle of a photon package ends when the package contains virtually no more luminosity. Typically we use the criterion that it must have lost 99.99% of its original luminosity, which immediately is the minimum level of absolute energy conservation of the simulation.

2.4.4 Peeling off and smart detectors

The goal of a Monte Carlo radiative transfer simulation is to simulate observable properties of a dusty system, i.e. images and spectral energy distributions. SKIRT uses the technique of peel-off photon packages to create an arbitrary number of images/SEDs at different observing positions. Peeling off is a Monte Carlo technique designed to create high signal-to-noise images (in particular scattered light images), adopted for the first time by Yusef-Zadeh et al. (1984) and included in almost all state-of-the-art Monte Carlo radiative transfer codes. After every emission or scattering event, the code calculates which fraction of the luminosity contained in the photon package would arrive at the observers' locations and at which point on the plane of the sky, if the photon package would be emitted or scattered in the appropriate propagation direction. Repeating this for every photon package at every emission or scattering event implies that the maximum available information is obtained for a fixed set of photon packages and hence strongly increases the signal-to-noise compared to the more simple Monte Carlo codes where only photon packages that leave the system are recorded.

Each SKIRT detector is basically an integral field detector, i.e. a data cube with two spatial and one wavelength dimension. In most Monte Carlo radiative transfer codes the simulated detectors are natural, idealised representations of actual CCD detectors (or a series of them at each wavelength). They basically consist of a two- or three-dimensional array of pixels, which act as a reservoir for the incoming photon packages. When a photon package leaves the system and arrives at the location of the observer, the correct pixel is determined and the luminosity of the photon package is added to the luminosity at that pixel. At the end of the simulation, the detector is read out pixel by pixel and the surface brightness distribution is constructed. While this approach seems the most natural way to simulate the detection of photon packages in a Monte Carlo simulation, it might not be the most efficient. We must be aware that, although we are simulating a real detection as closely as possible, we have more information at our disposal than real observers. The maximum information that a real observer can obtain (in the theoretical limit of perfect noise-free observations and instruments) when imaging with a CCD detector is the number of photon packages that arrive in each of his pixels. As numerical simulators, we have at our disposal the full information on the precise location of the impact of each photon package on the detector. In order to use this information, we have considered the concept of smart detectors, which take full advantage of the exact location of the impact of the incoming photon packages (Baes 2008). The principle of these smart detectors is based on the estimate of the density distribution in smoothed particle hydrodynamics simulations. While preserving the same effective resolution and having virtually no computational overhead, smart detectors realise a noise reduction of about 10 percent.

2.4.5 The dust emissivity

A crucial aspect of the SKIRT code is the calculation of the dust emissivity. From the stellar emission phase we know the total amount of absorbed radiation $L_{\lambda,m}^{\text{abs}}$ at each wavelength in each cell of the dust domain. From this absorption rate we can calculate the mean intensity of the ISRF $J_{\lambda,m}$ in each cell using

$$J_{\lambda,m} = \frac{L_{\lambda,m}^{\text{abs}}}{4\pi \kappa_{\lambda}^{\text{abs}} \rho_m V_m} \quad (2.29)$$

where $\kappa_{\lambda}^{\text{abs}}$ is the dust absorption coefficient, ρ_m is the dust density and V_m is the volume in cell number m respectively. Knowledge of the mean intensity and the dust properties in each cell allows the dust emissivity $j_{\lambda,m}^{\text{d}}$ to be determined. SKIRT contains three different modules for the calculation of the dust emissivity, depending on the physical processes that are taken into account.

Three different options for the dust emissivity

The simplest option is to consider the dust grains as a single species that is in local thermal equilibrium (LTE) with the local ISRF. In this case, the dust emits as a modified black-body radiator,

$$j_{\lambda,m}^{\text{d}} = 4\pi \rho_m V_m \kappa_{\lambda}^{\text{abs}} B_{\lambda}(T_m) \quad (2.30)$$

where the dust equilibrium temperature T_m of the m 'th dust cell is determined by the condition of thermal and radiative equilibrium,

$$\int_0^{\infty} \kappa_{\lambda}^{\text{abs}} J_{\lambda,m} d\lambda = \int_0^{\infty} \kappa_{\lambda}^{\text{abs}} B_{\lambda}(T_m) d\lambda. \quad (2.31)$$

The second, somewhat more realistic option is to still consider LTE for the dust grains, but taking into account that each species and size of dust grain reaches its own equilibrium temperature. The SKIRT code allows to consider dust mixtures with an arbitrary number of grain species and size distributions. The size distributions of the various dust species are subdivided into different bins, resulting in a dust mixture with N_{pop} populations, each of them corresponding to a dust species and a small size bin. Assuming LTE for each individual population, the dust emissivity is given by a sum of modified black-bodies, where the temperature of each population is still determined by the condition of thermal and radiative equilibrium,

$$j_{\lambda,m}^{\text{d}} = 4\pi \rho_m V_m \sum_{i=1}^{N_{\text{pop}}} \kappa_{\lambda,i}^{\text{abs}} B_{\lambda}(T_{m,i}) \quad (2.32)$$

with $\kappa_{\lambda,i}^{\text{abs}}$ as the contribution of the i 'th dust population to the total absorption coefficient $\kappa_{\lambda}^{\text{abs}}$, and $T_{m,i}$ the equilibrium temperature of the i 'th population in cell number m , determined by

$$\int_0^{\infty} \kappa_{\lambda,i}^{\text{abs}} J_{\lambda} d\lambda = \int_0^{\infty} \kappa_{\lambda,i}^{\text{abs}} B_{\lambda}(T_{m,i}) d\lambda. \quad (2.33)$$

The third option, in fact the only realistic option to model the spectral energy distribution of galaxies, is to consider NLTE dust emission. In theory, the transition from LTE to NLTE dust emission is not an enormous step. The main difference is that each dust population is not characterised by a single equilibrium temperature, but by a temperature distribution. Once the temperature distribution function has been determined, the dust emissivity can be easily determined. As argued in the introduction to this chapter, however, the practical inclusion of NLTE dust emission in radiative transfer codes is a notoriously hard nut to crack, but before going into the details of the implementation within SKIRT in Sections 2.6 and 2.7, the physics of NLTE dust emission and the mathematical derivation of its temperature distribution is discussed in the next Section.

2.5

Solving the temperature distribution of VSGs

As already explained in Chapter 1, very small grains can reach much higher temperature levels than the bigger grains. The same can be said about PAHs, fairly large, complex hydrocarbon molecules with at least tens of atoms, which can be considered as an extension of the grain populations size range at the smallest end. Their reduced size entails a smaller cross-section and therefore a lowered frequency of absorption events, leading to a time-dependent, irregular temperature behaviour (Figure 2.2). Moreover, due to their small size, these grains will primarily absorb photons with shorter wavelengths, compared to the situation for larger grains. Combined with the smaller heat capacities, again due to their smaller size, each individual absorption event by these small grains means an almost immediate excursion to much higher temperature levels and a subsequent, smooth cooling transition to the fundamental temperature level (see e.g. Draine 2003a; Krügel 2003). To calculate the dust emission caused by this stochastic heating, it is best to treat VSGs collectively as an ensemble.

When an ensemble of a certain type of very small dust grains is stochastically heated by the interstellar radiation field, it therefore no longer attains an equilibrium temperature as is the case for larger grain sizes. Instead, the temperatures of the individual grains in the ensemble now follow a temperature distribution with a specific probability density which is dependent on the radiation field and the physical characteristics of the grains. In fact, the equilibrium temperature for larger grains is a special case of

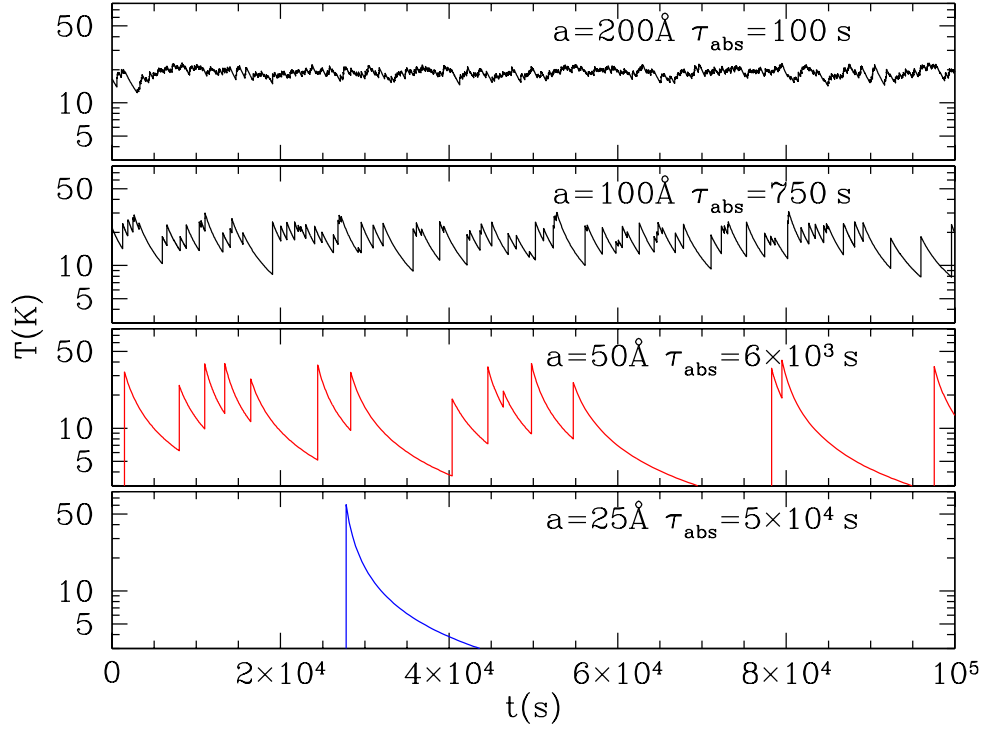


Figure 2.2: An overview of the temperature evolution over time for different grain sizes radiated by the same, average interstellar radiation field. The mean time interval τ_{abs} between absorption events dramatically increases with reduction in grain size (Draine 2003a).

this situation: their probability density is nearly equivalent to a δ -function $\delta(T_{\text{eq}})$ with T_{eq} the equilibrium temperature.

Although this temperature probability density $P(T)$ itself is obviously continuous, determining this density is usually done by discretising the problem: the temperature range is divided into several bins, and since the enthalpy of the grains $H(T)$ is only dependent on the temperature, the equivalent division is also applied to the latter. The different probabilities for the various temperature bins therefore form a vector of temperature states any random grain can find itself in at a specific time t . As outlined in Guhathakurta & Draine (1989), we can then define a transition matrix $A_{f,i}$ which describes the probability per unit time for a grain in an initial state i from such a vector of temperature states to be transferred to a final state f and calculate the rate at which grains are thus transferred between different states (with N the number of states):

$$\frac{d}{dt} \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_{N-1} \\ P_N \end{pmatrix} = \begin{pmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,N-1} & A_{1,N} \\ A_{2,1} & A_{2,2} & \cdots & A_{2,N-1} & A_{2,N} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ A_{N-1,1} & A_{N-1,2} & \cdots & A_{N-1,N-1} & A_{N-1,N} \\ A_{N,1} & A_{N,2} & \cdots & A_{N,N-1} & A_{N,N} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_{N-1} \\ P_N \end{pmatrix}, \quad (2.34)$$

where the diagonal elements of A are purely defined as:

$$A_{l,l} \equiv - \sum_{m \neq l}^N A_{m,l}. \quad (2.35)$$

As pointed out in Krügel (2003), each state l has a fraction of grains incoming from and a fraction going out to other states, both of which can be split into a cooling and a heating term:

$$\begin{aligned} P_{l,\text{in}} &= \sum_{m>l}^N A_{l,m} P_m + \sum_{m<l}^N A_{l,m} P_m = \sum_{m \neq l}^N A_{l,m} P_m \\ P_{l,\text{out}} &= P_l \underbrace{\sum_{m<l}^N A_{m,l}}_{\text{cooling}} + P_l \underbrace{\sum_{m>l}^N A_{m,l}}_{\text{heating}} = P_l \sum_{m \neq l}^N A_{m,l} \end{aligned} \quad (2.36)$$

For almost any practical application, only the steady state situation, which is in equilibrium for the ensemble as a whole, is required, which means the incoming and outgoing fractions of equation (2.36) must be equal to each other for all states, and which reduces the left hand side of equation (2.34) to zero:

$$\sum_{l=1}^N A_{m,l} P_l = 0. \quad (2.37)$$

Due to the definition of the diagonal elements, it can be easily shown that the determinant of matrix A is zero (e.g. by adding all other rows to the first, which leaves the determinant invariant, but results in an entire row of zeroes) and that therefore matrix A itself is clearly singular, reducing the homogeneous system of linear equations (2.37) to $N - 1$ linearly independent equations. The additional equation necessary to solve for all N unknowns $P_1, P_2, \dots, P_N$ is provided by the requirement that the probability density is normalised:

$$\sum_{l=1}^N P_l = 1. \quad (2.38)$$

The description of the matrix elements $A_{m,l}$ given in Krügel (2003) is based on frequency bins, but these are equivalent to enthalpy bins using the formula $H = h\nu$ with h being Planck's constant and ν the frequency, since both sides represent the same amount of energy. This description will be followed here, but since SKIRT uses a wavelength instead of a frequency grid during the course of every simulation, the equations for the matrix elements will be transformed to a more natural form for SKIRT, using wavelengths instead of frequencies.

For dust grains heated from state l to state m (with $l < m$), the matrix element $A_{m,l}$

is equal to the width of the final frequency bin $\Delta\nu_m$ multiplied by the total number of photons carrying the necessary energy $h(\nu_m - \nu_l)$ for the transition, which the particular type of grain absorbs from the interstellar radiation field per frequency and per time unit:

$$A_{m,l} = \frac{4\pi C_v^{\text{abs}} J_\nu}{h\nu} \Delta\nu_m \quad \nu = \nu_m - \nu_l \quad l < m, \quad (2.39)$$

with J_ν the mean intensity of the radiation field and C_v^{abs} the absorption cross-section for the type of grain, which is in itself given by $C_v^{\text{abs}} = \pi a^2 Q^{\text{abs}}(a, \nu)$, with a the radius of the grain and $Q^{\text{abs}}(a, \nu)$ the absorption efficiency as a function of radius and frequency.

This prescription for the matrix elements representing the heating transitions can now be transformed into a form using wavelengths and enthalpies instead of frequencies, using $\nu J_\nu = \lambda J_\lambda$ and

$$\begin{aligned} \lambda &= \frac{c}{\nu} \\ &= \frac{hc}{h(\nu_m - \nu_l)} \\ &= \frac{hc}{H_m - H_l}. \end{aligned} \quad (2.40)$$

This eventually leads to the following evaluation:

$$\begin{aligned} A_{m,l} &= \frac{4\pi C_v^{\text{abs}} J_\nu h}{h^2 \nu} \Delta\nu_m \\ &= 4\pi C_{\lambda(\nu)}^{\text{abs}} \frac{\lambda}{h\nu} J_\lambda \frac{\Delta H_m}{H_m - H_l} \\ &= 4\pi C_\lambda^{\text{abs}} J_\lambda \frac{hc \Delta H_m}{(H_m - H_l)^3} \quad \lambda = \frac{hc}{H_m - H_l} \quad l < m. \end{aligned} \quad (2.41)$$

The cooling of a dust grain from state l to state m (with $m < l$) has a similar matrix element, but instead of absorbing a radiation field, it emits photons itself as a black-body, following Planck's law:

$$A_{m,l} = \frac{4\pi C_v^{\text{abs}} B_\nu(T_l)}{h\nu} \Delta\nu_m \quad \nu = \nu_l - \nu_m \quad m < l \quad (2.42)$$

A similar transformation, this time using $\nu B_\nu(T_l) = \lambda B_\lambda(T_l)$ and $\lambda = \frac{hc}{H_l - H_m}$, can be applied:

$$\begin{aligned} A_{m,l} &= \frac{4\pi C_v^{\text{abs}} B_\nu(T_l) h}{h^2 \nu} \Delta\nu_m \\ &= 4\pi C_{\lambda(\nu)}^{\text{abs}} \frac{\lambda}{h\nu} B_\lambda(T_l) \frac{\Delta H_m}{H_l - H_m} \\ &= 4\pi C_\lambda^{\text{abs}} B_\lambda(T_l) \frac{hc \Delta H_m}{(H_l - H_m)^3} \quad \lambda = \frac{hc}{H_l - H_m} \quad m < l. \end{aligned} \quad (2.43)$$

As a result, the matrix $A_{m,l}$ in equation (2.34) can be interpreted as having all cooling matrix elements above the diagonal, while all those for heating are located below it.

Now according to the energy balance, the total cooling and heating rates for each state l can also be written as, with $\nu_{m,l} = |\nu_l - \nu_m|$:

$$\begin{aligned}\sum_{m < l}^N A_{m,l} h \nu_{m,l} &= \underbrace{\int_0^\infty 4\pi C_\nu^{\text{abs}} B_\nu(T_l) d\nu}_{\text{cooling}} \\ \sum_{m > l}^N A_{m,l} h \nu_{m,l} &= \underbrace{\int_0^\infty 4\pi C_\nu^{\text{abs}} J_\nu d\nu}_{\text{heating}}\end{aligned}\quad (2.44)$$

However, since dust grains radiate as modified black-bodies in the infrared, emitted photons carry away very little energy, meaning that the dust temperature is reduced only very slowly. The result is that cooling transitions only occur to the states directly below the initial state l . In practice, only the cooling transitions $l \rightarrow m = l - 1$ are considered, and all matrix elements above the main diagonal, apart from the elements $A_{l-1,l}$ are put to zero. This is termed the thermal continuous cooling approximation (Draine & Li 2001). In order to still satisfy the energy balance, the latter elements have to be rewritten:

$$A_{l-1,l} = \int_0^\infty \frac{4\pi C_\nu^{\text{abs}} B_\nu(T_l) d\nu}{h(\nu_l - \nu_{l-1})}, \quad (2.45)$$

which can be easily deduced from the equation (2.44). Once again transforming this equation results in:

$$A_{l-1,l} = \int_0^\infty \frac{4\pi C_\lambda^{\text{abs}} B_\lambda(T_l) d\lambda}{H_l - H_{l-1}}. \quad (2.46)$$

These expressions for the matrix elements are equivalent to the corresponding formulations given in Misselt et al. (2001) and Bianchi (2008), which also describe radiative transfer codes using wavelength bins.

The matrix from equation (2.34) then looks like this:

$$A = \begin{pmatrix} A_{1,1} & A_{1,2} & 0 & \cdots & \cdots & 0 \\ A_{2,1} & A_{2,2} & A_{2,3} & \ddots & & \vdots \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ A_{N-2,1} & A_{N-2,2} & A_{N-2,3} & \ddots & A_{N-2,N-1} & 0 \\ A_{N-1,1} & A_{N-1,2} & A_{N-1,3} & \cdots & A_{N-1,N-1} & A_{N-1,N} \\ A_{N,1} & A_{N,2} & A_{N,3} & \cdots & A_{N,N-1} & A_{N,N} \end{pmatrix} \quad (2.47)$$

This special form makes it especially easy and efficient to compute the values of P_l for $l = 1, \dots, N$ through a fast recursive substitution. As indicated in Guhathakurta &

Draine (1989), the very first step to achieve this, is to define:

$$X_l = \frac{P_l}{P_1} \quad (2.48)$$

(and consequently $X_1 = 1$), such that subsequently, based on (2.37):

$$\sum_{l=1}^N A_{m,l} X_l = 0, \quad (2.49)$$

from which the solution for X_l for $l = 1, \dots, N$ can be used to easily calculate the corresponding values for P_l :

$$P_l = \frac{X_l}{\sum_{m=1}^N X_m}, \quad (2.50)$$

which clearly satisfies the normalisation condition (2.38). The solution for X_l itself can be simply found through substitution from (2.49), using the thermal continuous cooling approximation:

$$X_l = \frac{-\sum_{m=1}^{l-1} A_{l-1,m} X_m}{A_{l-1,l}} \quad l = 2, \dots, N. \quad (2.51)$$

However, as described in Guhathakurta & Draine (1989), when X_l becomes very small, the limited precision of floating point numbers on computers can lead to numerical error, because the solution (2.51) contains one negative term ($A_{l-1,l-1} X_{l-1}$), which in such cases is nearly cancelled out by the total of the other positive terms, provoking roundoff errors which are detrimental to the accuracy of the value for X_l . To circumvent this complication, a slightly different approach was devised by Guhathakurta & Draine (1989): when considering a subset of states up to and including $l - 1$, a grain can only enter this subset by cooling down from state l to $l - 1$, while a grain from this subset can only leave it if a photon carrying enough energy heats it to a state beyond state $l - 1$ (if the photon is not sufficiently energetic, given the grain's original state, the grain cannot leave the subset). In the steady state regime, this is equivalent to (after dividing by P_1):

$$A_{l-1,l} X_l - \sum_{m=1}^{l-1} X_m \sum_{n=l}^N A_{n,m} = 0 \quad l = 2, \dots, N, \quad (2.52)$$

which leads to the following result:

$$X_l = \frac{\sum_{m=1}^{l-1} B_{l,m} X_m}{A_{l-1,l}}, \quad (2.53)$$

where $B_{l,m}$ is defined as:

$$B_{l,m} \equiv \sum_{n=l}^N A_{n,m} \quad l > m. \quad (2.54)$$

It is clear that this slightly different approach results in a calculation with all non-negative terms, thus without risk of terms canceling out each other and the associated accuracy issues. On top of this, the values of $B_{l,m}$ can easily be found with the following recursion:

$$B_{l,m} = B_{l+1,m} + A_{l,m} \quad l = 2, \dots, N-1 \quad l > m, \quad (2.55)$$

starting with $B_{N,m} = A_{N,m}$ for all $m < N$.

Using the general homogeneous system of linear equations (2.37), finding the solutions for the N unknowns $P_1, P_2, \dots, P_N$ would imply a Gaussian elimination, e.g. through the LU decomposition of the matrix A , which would require a number of calculations of the order $\mathcal{O}(N^3)$. However, the scheme described above, using the thermal continuous cooling approximation, reduces the number of computations to an order $\mathcal{O}(N^2)$ problem.

From the definition of $B_{l,m}$ in (2.54), it is clear that a total number of $\frac{N(N-1)}{2}$ values have to be found (equivalent to the number of elements below the diagonal in the matrix A), but given the recursion relation (2.55), the total number of additions required for all $B_{l,m}$ values is only $\frac{(N-1)(N-2)}{2}$. Calculating the X_l values from (2.53) demands a further $\frac{(N-1)(N-2)}{2}$ additions, $\frac{N(N-1)}{2}$ multiplications and $(N-1)$ divisions. In solving for the desired P_l values, a final $(N-1)$ additions and N divisions have to be performed. This brings the grand total of arithmetic computations for solving the stochastic heating problem for a specific type and size of grain to $(N-1)^2$ additions, $\frac{N(N-1)}{2}$ multiplications and $(2N-1)$ divisions.

This result does not include the computations in calculating the individual necessary $A_{l,m}$ matrix elements, which do not scale with the number of enthalpy bins N , except for the cooling elements if the integration in (2.46) would be performed over the equivalent wavelength bins, but given the fact that there are only $(N-1)$ of these elements and the integration only scales with N , the total contribution of these computations would still only be at most of the order $\mathcal{O}(N^2)$.

As pointed out in Bianchi (2008), quite a few of the necessary calculations for the $A_{l,m}$ elements are common for a given chemical type of grain and can be tabulated to be used for the various grain sizes, provided a fixed set of temperature and enthalpy bins is used for all types. This can further reduce the total amount of necessary computations over the whole course of a radiative transfer simulation. However, this approach carries its own risks: as the grain size increases, its temperature distribution will more and more resemble the $\delta(T_{\text{eq}})$ -function. This becomes almost impossible to properly

sample using fixed temperature bins, especially since T_{eq} depends on the ISRF and is therefore not known a priori.

2.6

Implementation in SKIRT

The recursive recipe to calculate the temperature distribution for a particular grain type and size was implemented almost exactly as described in the previous Section, with the aim to include it within SKIRT. The only major difference is in calculating the matrix elements for the heating and cooling transitions of equations (2.41) and (2.46): since the individual equations of a homogeneous system of equations can be multiplied by a constant factor as desired, the forefactor 4π was dropped, the absorption coefficients $\kappa_{\lambda}^{\text{abs}}$ instead of the absorption cross-sections C_{λ}^{abs} were used since the former are directly accessible from the dust mix in a SKIRT simulation — and both are proportional to each other, as well as to the absorption efficiencies Q_{λ}^{abs} — and the factor hc was removed from the numerator of the $\frac{N(N-1)}{2}$ heating transition $A_{l,m}$ matrix elements of equation (2.41), to be moved to the denominator of the $(N-1)$ cooling transition $A_{l-1,l}$ elements of equation (2.46). The integration of the latter equation is approximated with the midpoint rectangle integration method over the global wavelength grid of the SKIRT simulation.

After performing the calculations for various grain sizes, the results are compared with those in Guhathakurta & Draine (1989) and Misselt et al. (2001) in Figures 2.3, respectively 2.4 and 2.5 respectively. Although these results appear to be consistent with each other, calculating the full spectral energy distributions of the dust emission based on these temperature distributions for a more complicated mixture of graphite and silicate grains, as well as PAHs, seems to draw a more problematic picture. These SEDs for a Draine & Li (2007) dust mixture irradiated by an average Galaxy ISRF, scaled with a factor U , are compared with the corresponding results from Bianchi (2008) in Figure 2.6. It appears that in the implementation intended for SKIRT, the peaks caused by the PAHs are not quite at the position they are supposed to be found and their intensities are differing rather dramatically from their proper values. On top of that, the emission in the MIR to FIR range seems to indicate the small grains do not attain the higher temperatures of the Bianchi (2008) SEDs.

Even though there are any number of factors which might contribute to this differing behaviour, finding the root cause of it would probably not be that difficult. However, the computational time of the code is still too high to be used in 3D simulations: for a typical dust model consisting of three or four dust species each with their size distribution, the calculation of the emissivity for a single ISRF takes typically of the

order of several to tens of seconds on a standard desktop/laptop computer. While this is compatible with 1D or 2D simulations with up to 10^4 cells, this is excessively long to be used in each cell for general 3D simulations for which we have designed SKIRT. Therefore it would be useful to consider a different approach, using a library of various possible dust emission SEDs, which will now we discussed in the following Section.

2.7

A library approach for NLTE dust emission

Rather than use the implementation described in the previous Sections to calculate the NLTE emission for transiently heated grains, it was opted to couple the SKIRT code to the DustEM code (Compiègne et al. 2011). DustEM is a publicly available, state-of-the-art numerical tool designed to calculate the NLTE emission and extinction of dust given its size distribution, optical and thermal properties. The code builds on the work by Desert et al. (1986, 1990) and uses an adaptive temperature grid on which the temperature distribution of the grains is calculated iteratively. No LTE approximation is made, i.e. even for large grains the temperature distribution is calculated explicitly. One of the advantages why we have chosen to couple SKIRT to the DustEM code is that the latter code has been designed to deal with a variety of grain types, structures and size distributions and that new dust physics (ionisation of PAHs, polarised emission, spinning dust emission, temperature-dependent dust emissivity) can easily be included. On the other hand, a consequence of choosing for a very complete and accurate NLTE routine in which basically no simplifications or assumptions have been made, is that the computation load is substantial. Much like the specific implementation for VSGs described in the previous Section, it takes DustEM several seconds on a normal desktop or laptop to perform the necessary calculations for a single ISRF with a characteristic dust model.

To overcome this problem, we have adopted a strategy based on a library of dust emissivity profiles, inspired by the work of Juvela & Padoan (2003). Their approach consists of three steps: they first run an exploratory radiative transfer simulation on a grid with a reduced number of grid cells, without taking dust re-emission into account. This low-resolution simulation is used to determine the range of ISRFs encountered in the simulation. The second step consists of picking a small number N_{ref} of reference wavelengths λ_i^{ref} (typically $N_{\text{ref}} = 2$). The different ISRFs found in step one are discretised onto logarithmic intervals at each of the reference wavelengths, and at each bin in the N_{ref} -dimensional parameter space, the full NLTE dust emission spectrum is calculated and stored in a library. The final step in the simulation consists of running a radiative transfer simulation at the full resolution. The dust emissivity at any given cell is found

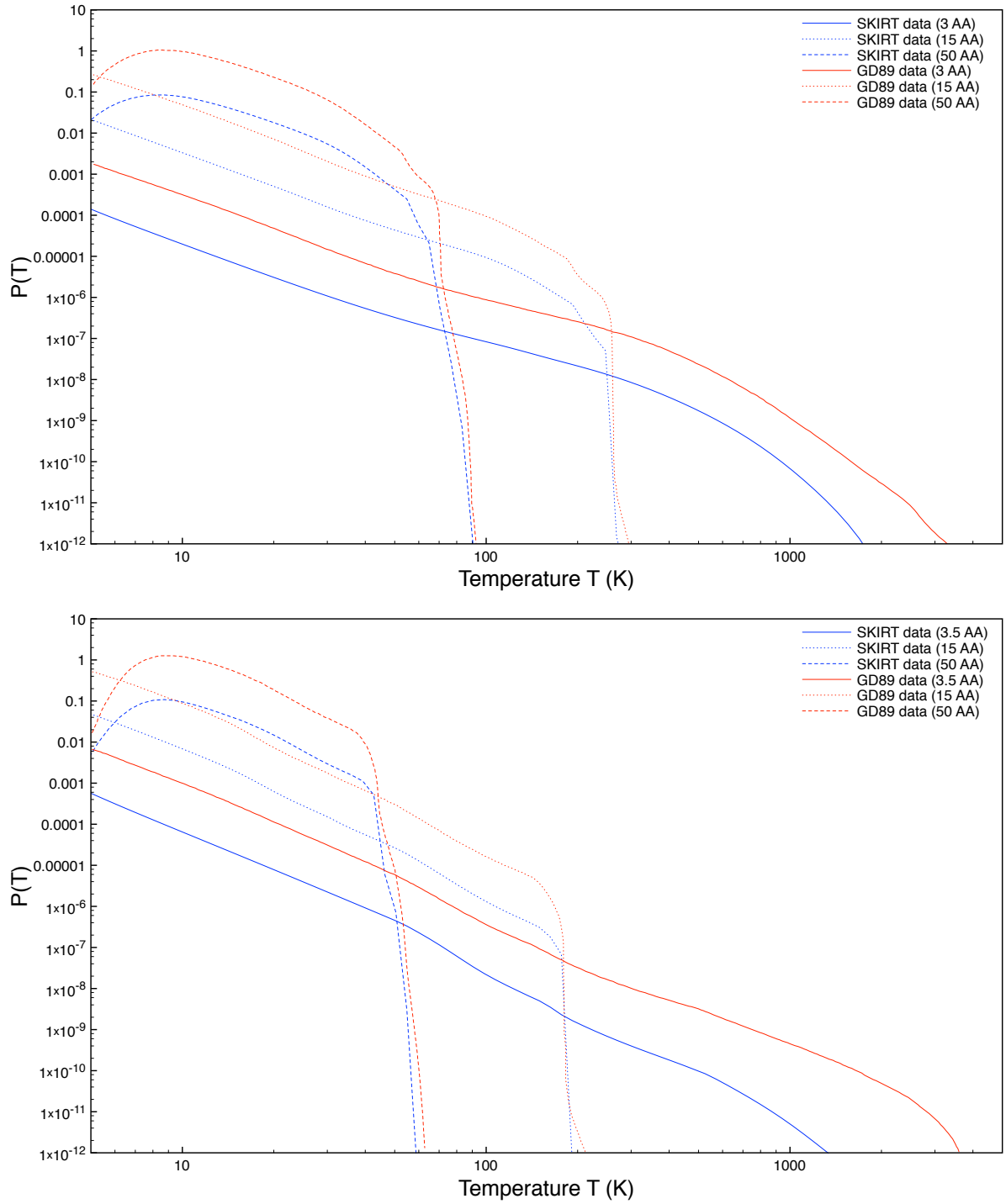


Figure 2.3: Comparison of VSG temperature distributions as given in Guhathakurta & Draine (1989) (red) with the solutions using the implementation for SKIRT (blue), for carbonaceous (*top*) and silicate (*bottom*) grains. The vertical shift can be explained by the fact that the distributions in Guhathakurta & Draine (1989) are not strictly normalised.

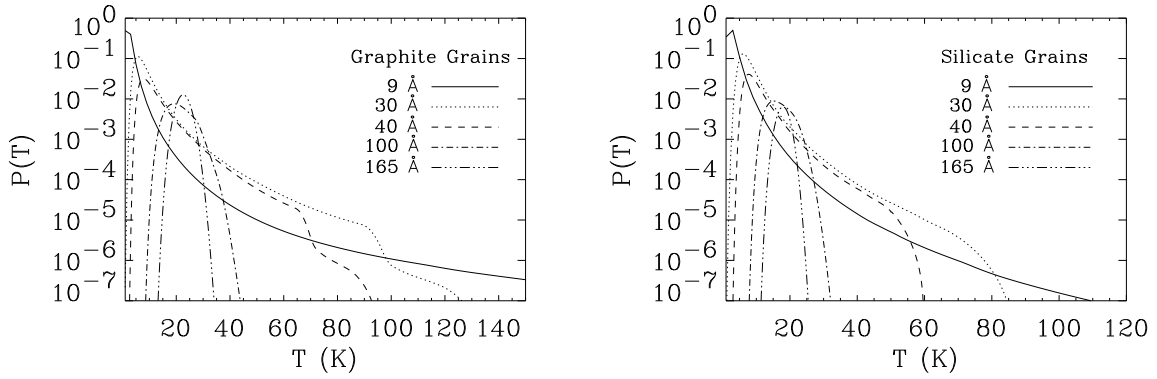


Figure 2.4: VSG temperature distributions as given in Misselt et al. (2001), for carbonaceous (*left*) and silicate (*right*) grains.

by looking at the ISRF at the N_{ref} reference wavelengths and interpolating the dust emissivities from the library.

While valuable and inspiring, we see two drawbacks in the method as implemented by Juvela & Padoan (2003). In panchromatic radiative transfer simulations of galaxies, we typically solve the transfer equation at many UV/optical wavelengths, and hence have the ISRF at all these wavelengths at our disposal at every grid cell. It would be a pity not to use this information to determine the dust emissivity and only base our estimate on the value of the ISRF at a very small number of reference wavelengths. In particular, the ISRF in Monte Carlo simulations can be noisy in certain cells; when the dust emissivity is determined based on the value of the ISRF at a small number of reference wavelengths, this noise could lead to a significant error. Using an estimate that exploits the available information at all wavelengths can minimise this error.

The second drawback is that the library method of Juvela & Padoan (2003) requires an exploratory, low-resolution simulation in which the parameter space of ISRFs is explored and the library of dust emissivities is built. This extra simulation not only requires a computational overhead, it also creates the danger that it does not cover the entire range of strengths and shapes of the ISRF. For example, one can assume that the strongest ISRF in a simulation is found in small dust cells very close to the heating sources. In a low-resolution simulation, with larger dust cells, this strong ISRF will be smoothed over the larger grid cells. Similarly, the weakest ISRF (or equivalently, the coldest dust) in some simulations could be found in the inner regions of dense cores, and due to smoothing a low-resolution simulation might not reach these weakest ISRF levels. The result is that the low-resolution grid will not cover the full range of ISRFs encountered in the high-resolution grid, and hence that the library of dust emissivities must be somehow extended to incorporate this missing part in the parameter space.

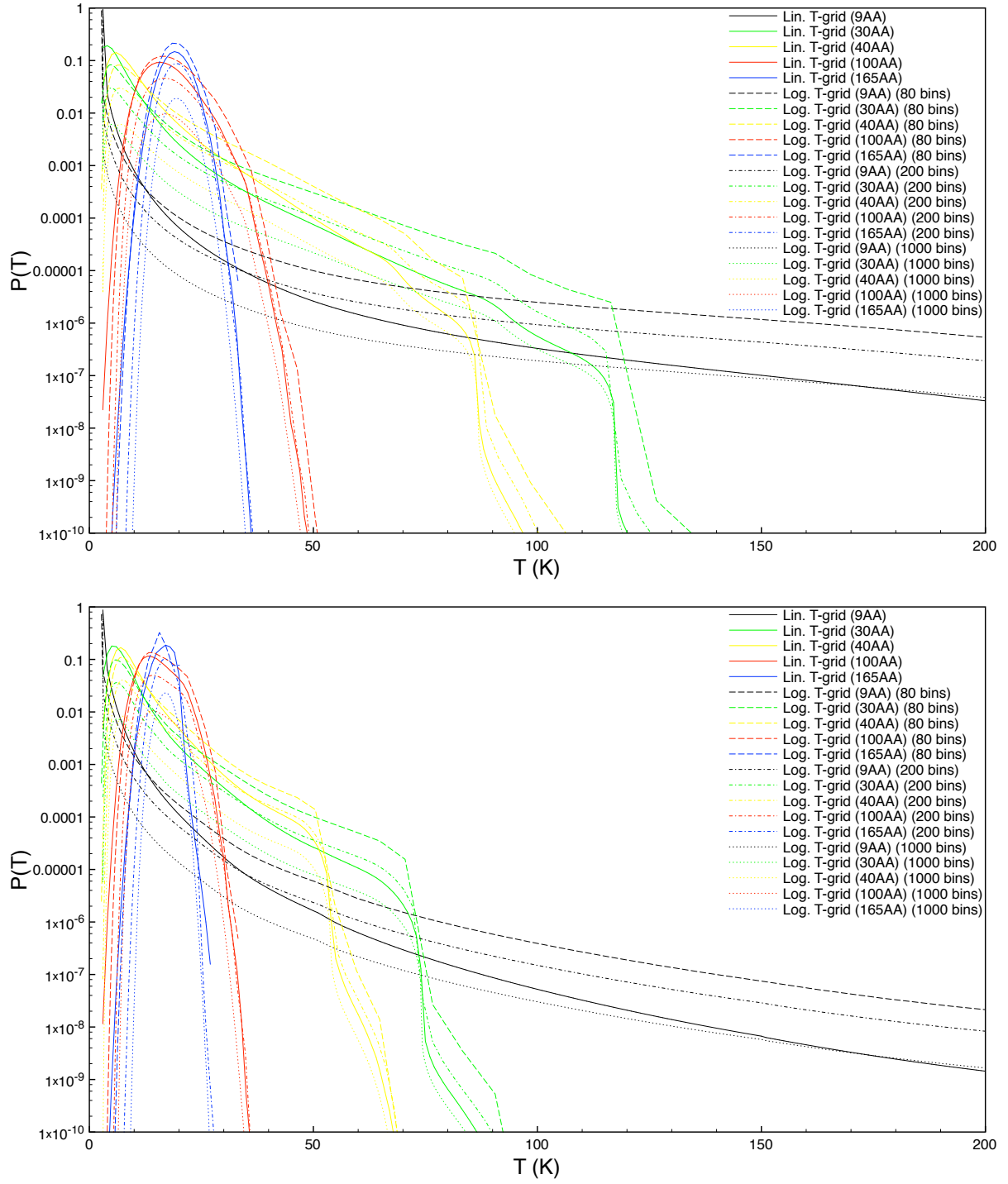


Figure 2.5: Solutions of VSG temperature distributions using the implementation for SKIRT, for carbonaceous (*top*) and silicate (*bottom*) grains, to be compared with the solutions in Figure 2.4, taken from Misselt et al. (2001). At the same time, the effect of different temperature binning choices is demonstrated, for grain sizes ranging from 9 Å to 165 Å.

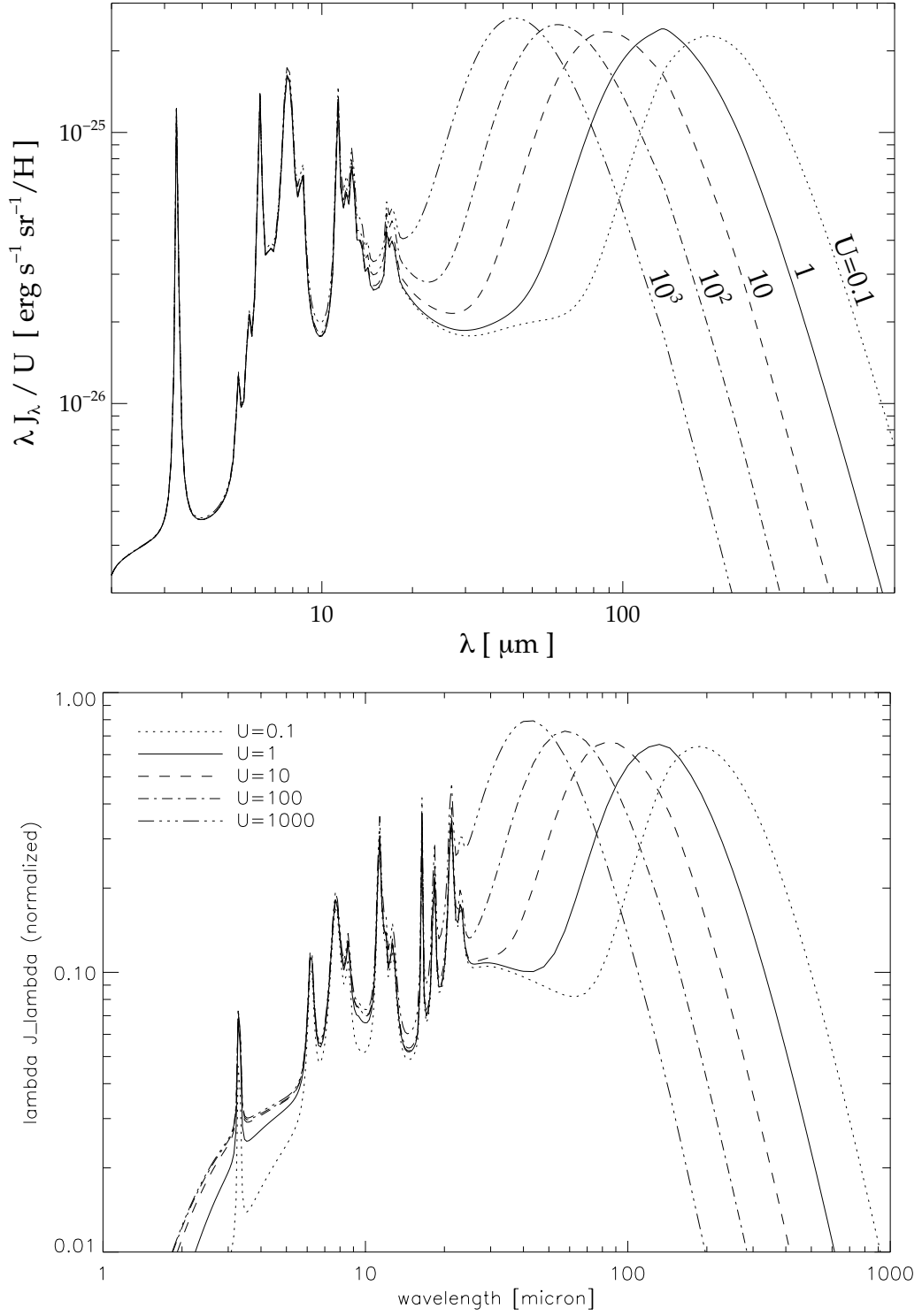


Figure 2.6: Comparison of the calculated dust emission spectral energy distributions for a Draine & Li (2007) dust mixture of carbonaceous and silicate grains in an average Galaxy ISRF multiplied by various scaling factors U , as performed in Bianchi (2008) (*top*) and with the implementation intended for SKIRT (*bottom*).

Juvela & Padoan (2003) are aware of this inconvenience (they discuss only the coldest spectrum as they concentrate on dark clouds illuminated by an external radiation field). They argue that this problem is not expected to be significant, and that it could be relieved by using a low-resolution simulation with a slightly higher density. Still, it is clear that the use of a low-resolution grid leads to an additional overhead and complication and is a potential source of error, and it would be better to avoid it.

To overcome both problems, we have taken a slightly different approach to implement our dust emissivity library. The first step in our library approach is to calculate a number of parameters that characterise the ISRF in each dust cell after the stellar emission phase. Instead of the value of J_λ at a number of wavelengths, we use parameters that use combined information at all available wavelengths. From the various range of possibilities, we choose the lowest-order moments of $\kappa_\lambda^{\text{abs}} J_\lambda$, the product of the ISRF and the dust absorption coefficient. Instead of the actual zeroth-order moment or normalisation of this function, we consider the equivalent would-be equilibrium dust temperature T_{eq} of the dust mixture, found by solving the equation

$$\int_0^\infty \kappa_\lambda^{\text{abs}} B_\lambda(T_{\text{eq}}) d\lambda = \int_0^\infty \kappa_\lambda^{\text{abs}} J_\lambda d\lambda \quad (2.56)$$

As a second parameter, we take the first-order moment $\kappa_\lambda^{\text{abs}} J_\lambda$, i.e. the mean wavelength,

$$\bar{\lambda} = \frac{\int_0^\infty \kappa_\lambda^{\text{abs}} J_\lambda \lambda d\lambda}{\int_0^\infty \kappa_\lambda^{\text{abs}} J_\lambda d\lambda} \quad (2.57)$$

In SKIRT we limit ourselves to two parameters, but in principle this procedure can be extended to more parameters.

With T_{eq} and $\bar{\lambda}$ calculated in each dust cell, we construct a 2D rectangular grid with $N_{T_{\text{eq}}} \times N_{\bar{\lambda}}$ pixels in the $(T_{\text{eq}}, \bar{\lambda})$ parameter space, based on the range of values encountered in the present simulation. In every parameter space pixel we construct a reference ISRF by averaging all ISRFs that correspond to those particular values of T_{eq} and $\bar{\lambda}$. We experimented with different ways of averaging, including taking the straight mean, the median or the mean using sigma-clipping, but found no noticeable difference. The final step of the library construction is to feed the reference ISRFs to the DustEM routine, and save each of the resulting dust emissivity profiles in the library.

Once the library is constructed, finding the correct dust emissivity for a given dust cell is straightforward, as each dust cell is already connected to a certain pixel in the $(T_{\text{eq}}, \bar{\lambda})$ parameter space and hence a dust emissivity profile in the library.

We have run extensive tests to check the accuracy of the SKIRT code against other radiative transfer codes. The early versions of the code were already tested against several other results, most importantly the set of spiral galaxy models by Byun et al. (1994) (see e.g. Baes et al. 2003). We have successfully tested the LTE version of SKIRT against the 1D and 2D LTE circumstellar benchmark problems of Ivezić et al. (1997) and Pascucci et al. (2004). SKIRT is also one of the codes used in a new ongoing LTE benchmark effort focusing on a disc galaxy environment (Baes et al., in preparation). The preliminary results, based on the results from five independent radiative transfer codes indicate excellent agreement, with relative differences in the SEDs around the 1% level or even below.

As a full NLTE radiative transfer benchmark is not (yet) available at the moment, we have tested our NLTE radiative transfer code, and particularly the library approach, using different models with gradually increasing levels of complexity. In order to run simulations in a realistic setting, we adopt the Sbc galaxy UGC 4754 as a template model. UGC 4754 is a edge-on spiral galaxy, which has always been a favorite class of galaxies for radiative transfer modellers, as the dust is clearly visible both in absorption and emission (e.g. Xilouris et al. 1997, 1998, 1999; Popescu et al. 2000a, 2011; Misiriotis et al. 2001; Dasyra et al. 2005; Bianchi 2007, 2008). This galaxy was one of the first large edge-on galaxies to be observed with the *Herschel Space Observatory* as part of the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS, Eales et al. 2010) Science Demonstration Phase observations. In Baes et al. (2010b), we fitted a radiative model to the observed images of UGC 4754 in the SDSS and UKIDSS bands. We subsequently used the SKIRT code to predict the galaxy’s SED and images at FIR wavelengths. While the radiative transfer model used in that paper was sufficient to serve its goal (investigation of the dust energy balance), it suffered from two significant limitations: the assumptions of LTE dust emission and of a smooth interstellar medium. These two assumptions prevented us from making a self-consistent model covering the entire spectral region from the UV to mm wavelengths. Moreover, they also might introduce a significant source of uncertainty, as it has been demonstrated by several authors that the extinction properties of a clumpy interstellar medium can be significantly different from those of a smooth medium (e.g. Hobson & Scheuer 1993; Witt & Gordon 1996, 2000; Wolf et al. 1998; Bianchi et al. 2000b; Matthews & Wood 2001; Pierini et al. 2004; Doty et al. 2005).

In this Section we will gradually refine our model for UGC 4754 from a smooth, 2D, LTE model to a fully 3D model that includes NLTE dust emission and a clumpy struc-

ture of the dusty ISM. The main objectives are to test the accuracy of our approach using a realistic setting, and to demonstrate the ability of SKIRT to run realistic 3D NLTE radiative transfer calculations. For a full investigation of the dust energy balance in spiral galaxies, based on our refined SKIRT code and multi-wavelength imaging data, we refer to future work.

2.8.1 2D radiative transfer models

The starting point for our models is the best fitting, smooth 2D model from Baes et al. (2010b). The stellar distribution consists of two components: a double-exponential stellar disc with a scalelength of 4.05 kpc and a scaleheight of 330 pc, and a flattened Sérsic bulge with a major axis effective radius of 800 pc, a Sérsic parameter of 0.9 and an intrinsic flattening of 0.6. Both components have a similar intrinsic SED, corresponding to a population of 8 Gyr old with an exponentially decaying star formation rate and an initial burst duration of 0.15 Gyr. The total bolometric luminosity of the system is $1.8 \times 10^{10} L_{\odot}$, of which the bulge contributes 8%. The dust is also distributed in a double-exponential disc with a scalelength of 6.1 kpc and a scaleheight of 270 pc. The total amount of dust is characterised by the *g*-band edge-on optical depth of 0.73, which corresponds to a total dust mass of $1.0 \times 10^7 M_{\odot}$. Contrary to Baes et al. (2010b) where we used the Zubko et al. (2004) model to describe the dust optical properties, we now use the Draine & Li (2007) dust model, as this model is embedded in the DustEM library (Compiègne et al. 2011).

Simulations are run on a wavelength grid with 181 grid points, with 101 grid points distributed logarithmically between 0.05 and 5000 μm and 80 additional grid points distributed logarithmically between 1 and 30 μm to capture the PAH peaks. For our 2D simulations, we considered an axisymmetric grid with 51 grid points in the radial direction and 51 grid points in the vertical direction, resulting in a total number of $N_{\text{cells}} = 2500$ grid cells. The grid points are chosen to have a power-law distribution, with an extent of 30 kpc (2 kpc) for the radial (vertical) distribution and a size ratio of 30 between the innermost and outermost bins. In all SKIRT runs discussed here, we used 10^6 photon packages for each wavelength in both the stellar and the dust emission phase.

Figure 2.7 shows the resulting SEDs of two different SKIRT 2D simulations based on this model setup, as well as the observed *Galaxy Evolution Explorer* (GALEX), SDSS, UKIDSS, *IRAS* and *Herschel* fluxes for UGC 4754. The blue curve shows the SED corresponding to a model assuming LTE dust re-emission, where we took into account that different grain types and sizes reach different equilibrium temperatures. The black curve shows the SED of the model that includes NLTE dust re-emission using the li-

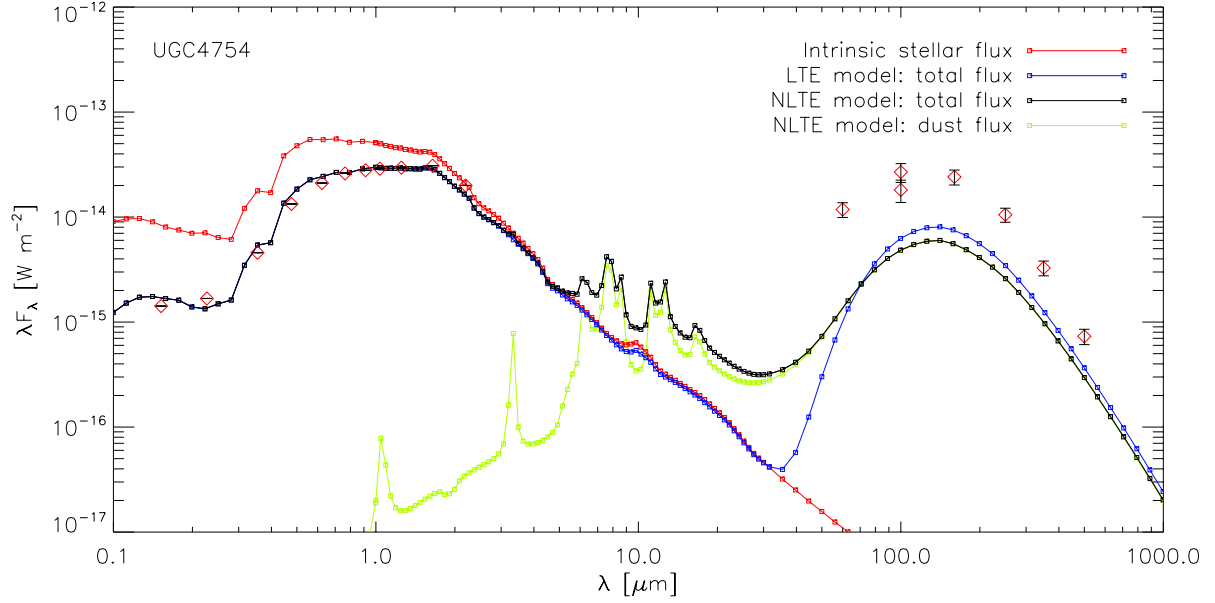


Figure 2.7: SEDs of the SKIRT 2D models for UGC 4754. The blue curve corresponds to a model assuming LTE dust re-emission, the black curve shows the SED of the model that includes NLTE dust re-emission. For the latter model, the yellow line shows the contribution of the thermal dust emission to the SED. The red curve represents the intrinsic flux of the model without dust extinction, and the data points are the observed total fluxes of UGC 4754.

brary approach discussed in Section 2.4.5. The red curve represents the flux of the model without dust extinction, the yellow line corresponds to the contribution of the dust to the SED in the NLTE case. It is logical that there is no difference between the LTE and NLTE models in the UV/optical/NIR part of the SED, as only the dust emissivity differs between the models. There is, however, a significant difference between the LTE and NLTE models in the MIR/FIR/sub-mm window: in the LTE models, all absorbed radiation is re-emitted as modified blackbody emission in the FIR/sub-mm region, whereas the NLTE models emit part of the absorbed radiation in the MIR region.

To test the accuracy of our library approach, we ran a second NLTE simulation, where we did not use the library approach, but where we calculated the dust emissivity in each cell by an explicit call to the DustEM code. The relative difference between the SEDs of the SKIRT NLTE models using the library approach and the brute force approach is shown in Figure 2.8. This figure convincingly shows that the library approach is accurate: the relative error is everywhere below 0.2% and in the region where the dust emission dominates even smaller. The difference in run time between the two approaches is substantial, and this difference is only due to the difference in the number of calls to the DustEM routine. In the brute force approach, the number of calls is obviously equal to N_{cells} (or sometimes a bit less if there are empty dust cells). The

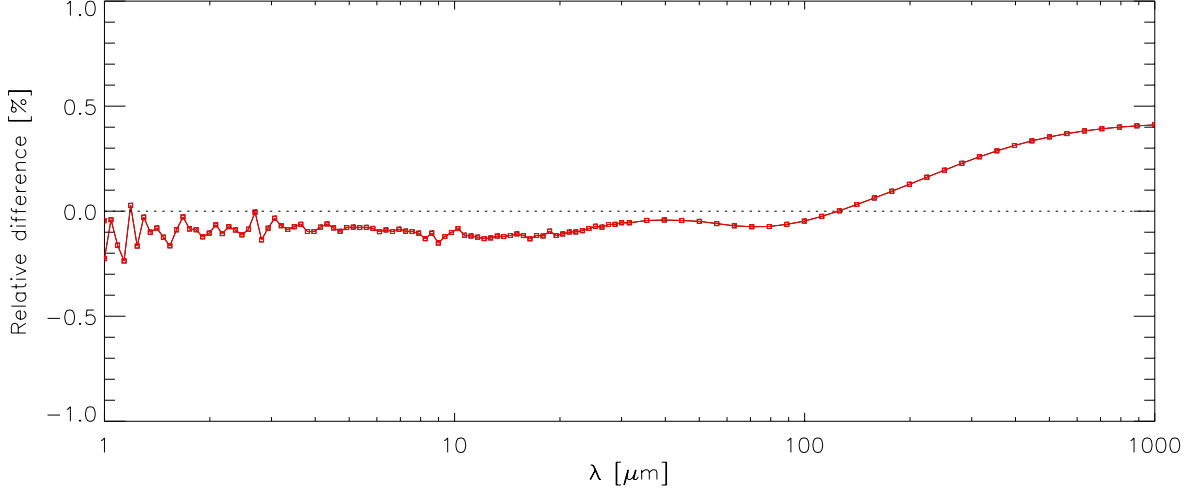


Figure 2.8: The relative difference $(F_{\lambda}^{\text{bf}} - F_{\lambda}^{\text{lib}})/F_{\lambda}^{\text{lib}}$ between the dust SEDs of 2D NLTE models for UGC 4754 using the brute force (bf) approach and the library (lib) approach.

maximum number of calls to the DustEM routine in the library approach is obviously $N_{T_{\text{eq}}} \times N_{\bar{\lambda}}$, the number of pixels in the library parameter space. As the intensity of the ISRF is the main parameter that drives the shape of the dust emissivity spectrum (Draine & Li 2001; Compiègne et al. 2011), it is appropriate to choose $N_{T_{\text{eq}}}$ somewhat larger than $N_{\bar{\lambda}}$; the values we propose are $N_{T_{\text{eq}}} = 25$ and $N_{\bar{\lambda}} = 10$. This infers a maximum of 250 calls to the DustEM routine. In most cases, however, not the entire $(T_{\text{eq}}, \bar{\lambda})$ parameter space is covered, such that the number of calls is even further reduced. In the present simulation, we needed to call the DustEM routine only 71 times in the library approach, compared to 2500 times in the brute force approach. Given that the average DustEM run time is about 7 s (on a typical desktop computer) and that the overhead of the construction of the library is negligible, this makes a substantial difference. It should be noted that 2500 calls is still a very manageable number, but the brute force approach becomes impossible when moving to 3D grids with several million cells. For example, for a simulation with ten million dust cells, we would need a DustEM computation time of more than 2 years on a single core computer, compared to several minutes using the library approach.

As a final test and a demonstration of the necessity of our library approach, we ran our 2D simulation again, but now using a set of precomputed template emissivity profiles. In a sense this mimics the approach taken by e.g. Wood et al. (2008), although their approach is somewhat different as they calculate the emission by big grains using the LTE approximation and only use a template for the small grains. The basic idea of our template approach is that the dust emissivity from a cell depends only on a single parameter U , being the integrated mean intensity of the ISRF in the considered cell

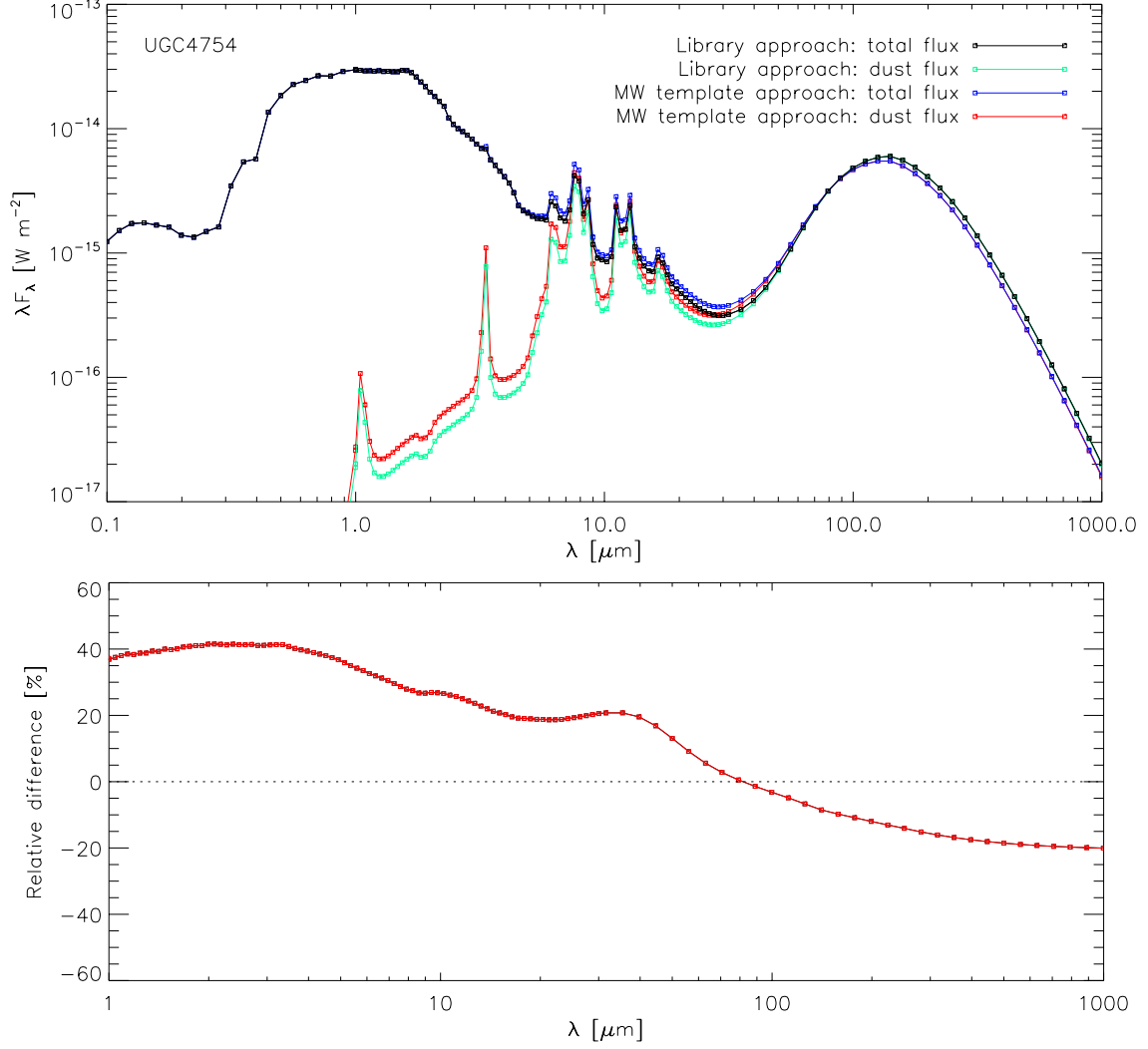


Figure 2.9: Comparison of our library approach and the Milky Way ISRF template approach for 2D NLTE models for UGC 4754. *Top:* The total SEDs and the dust emission SEDs corresponding to both approaches. *Bottom:* The relative difference $(F_\lambda^{\text{tem}} - F_\lambda^{\text{lib}}) / F_\lambda^{\text{lib}}$ between the dust SEDs using the MW ISRF template (tem) approach and our library (lib) approach.

expressed in terms of the integrated mean intensity of the ISRF in the Milky Way,

$$U = \frac{\int_0^\infty J_\lambda d\lambda}{\int_0^\infty J_\lambda^{\text{MW}} d\lambda} \quad (2.58)$$

For the ISRF of the MW, the standard parametrisation of Mathis et al. (1983) is adopted. We constructed a library of 501 dust emissivity profiles, corresponding to values of U distributed logarithmically between $U_{\min} = 10^{-5}$ and $U_{\max} = 10^5$. These dust emissivity profiles can be computed once and for all (using the DustEM routine) and saved in a file. In the dust emission phase, we simply calculate U in every dust cell and determine the dust emissivity profile using logarithmic interpolation between the precomputed

library profiles. This approach definitely has a strong appeal: it is straightforward to implement and very fast, as it requires only the calculation of U and a simple interpolation of precomputed values. In this sense it is more attractive than our library approach, which requires the construction of a library for every simulation. The disadvantage of the template approach, however, is that only the strength and not the shape or hardness of the ISRF is taken into account to calculate the dust emissivity. As also argued by Jonsson et al. (2010), the shape of the ISRF can have a significant importance, both because of the differing cross-sections of grains of different sizes and because high-energy photons will excite larger thermal fluctuations than low-energy photons for a given value of U .

In Figure 2.9 we show the comparison of the fixed template approach and our dynamic library approach (dynamic in the sense that the library is tailored to the specific simulation). The top panel shows the total SED and the dust emission SED for our 2D model for UGC 4754 obtained using both approaches. At first sight, the SEDs agree fairly well (definitely when plotted in log-log scale). Looking at the bottom panel, where we plot the relative difference of the dust emission SED corresponding to both approaches, we do see a significant difference, with relative deviations up to more than 40%. Here we have to give an important side note, in the sense that we believe that this 40% difference is actually a underestimate of the error one can make. The shape of the intrinsic SED of the stellar population in our model is independent of position; as a result, the variations in the shape of the ISRF in different cells in the simulation are only the result of varying levels of absorption and scattering. Since the stellar population model we adopted for UGC 4754 (an 8 Gyr old population with an exponentially decaying star formation rate and an initial burst duration of 150 Myr) is not very different from the average stellar population in the Milky Way, this implies that the shape of the ISRF in the different cells in our model will on average be quite close to the shape of the Milky Way ISRF. As far as the comparison between our library approach and the Milky Way template approach concerns, we must hence conclude that UGC 4754 simulations are not the strongest test. For systems with ISRFs which deviate much more from the average Milky Way ISRF, such as starburst galaxies or circumstellar discs around young hot stars, we expect much larger differences than the 40% we obtained here.

2.8.2 3D clumpy radiative transfer models

Having tested the accuracy of our library approach, we are ready to run full-scale 3D NLTE radiative transfer models with SKIRT. The first 3D model we consider has exactly the same set-up as the 2D NLTE model, except that we now consider a uniform 3D cartesian grid. In the x and y directions we consider 401 grid points each and a max-

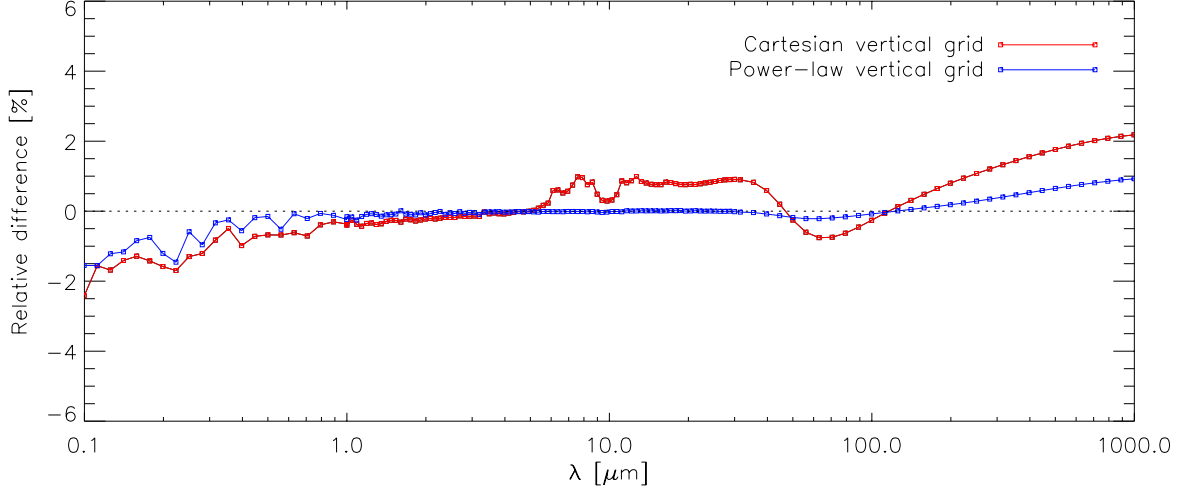


Figure 2.10: The relative difference $(F_{\lambda}^{3D} - F_{\lambda}^{2D})/F_{\lambda}^{2D}$ between the SEDs of 2D and 3D NLTE models for UGC 4754. The red curve corresponds to a 3D model with a uniform cartesian dust grid in all three dimensions, the blue curve corresponds to a 3D model with a power-law grid in the vertical direction, similar to the vertical grid structure of the 2D model.

imum extent of 30 kpc, in the vertical direction we use 61 grid points with a maximum extent of 2 kpc. This results in $N_{\text{cells}} = 9.6 \times 10^6$ grid cells, each with a dimension of 150 pc in the x and y directions and 66.7 pc in the vertical direction. Note that we need to store, at each dust grid cell, the entire ISRF J_{λ} at each of the wavelength grid points, which basically turns our grid into a 4-dimensional grid structure with 1.73×10^9 grid cells. The memory required to run such a large-scale SKIRT radiative transfer simulation is about 23 GiB.

Figure 2.10 compares the SED of the smooth 2D and 3D models for UGC 4754. The relative differences are below 2% in the entire UV-mm domain. The existing small differences are mainly due to the discretisation of the grid in the vertical direction: for the 2D model we used a vertical grid with a power-law distribution, with smaller bins close to the equatorial plane, where the dust density has the strongest gradients. The innermost grid cell has a height of only 8.75 pc, compared to the 66.7 pc in the case of the 3D grid. The result is that the discretisation of the dust density on the 3D grid is much coarser. To demonstrate that this vertical grid distribution is the origin of this $< 2\%$ difference, we ran another 3D simulation where we now apply the same power-law distribution for the vertical grid cells as we did for the 2D model. The relative differences between the SED of this model and the SED of the 2D simulation are also indicated in Figure 2.10.

The reason why we considered a uniform cartesian dust grid is because such a grid forms the basis for a fully 3D model with a clumpy, two-phase dust distribution. To generate such a model, we followed the strategy outlined by Witt & Gordon (1996). The

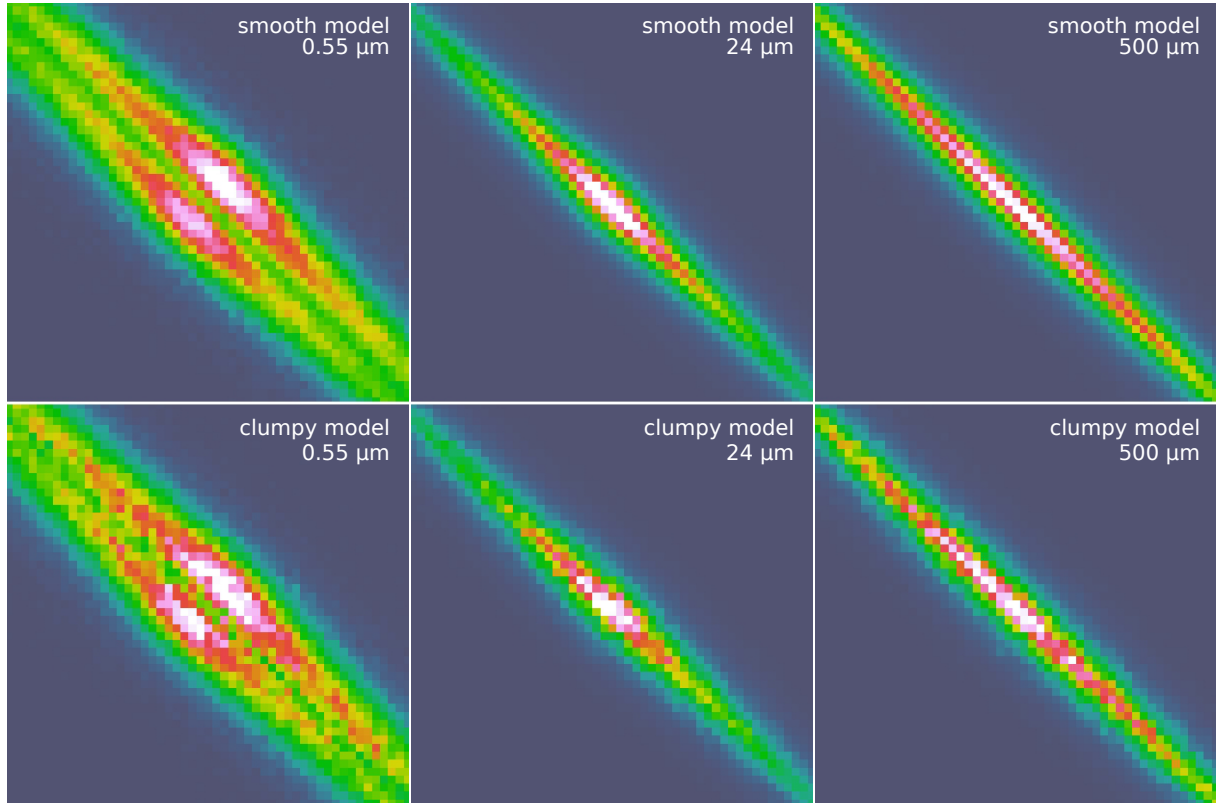


Figure 2.11: Simulated images corresponding to the smooth (*top row*) and clumpy (*bottom row*) 3D models for UGC 4754. The three panels correspond to three different regimes: stellar emission and dust extinction ($0.55\ \mu\text{m}$, *left*), NLTE emission by small grains ($24\ \mu\text{m}$, *middle*) and LTE emission by big grains ($500\ \mu\text{m}$, *right*).

dusty interstellar medium consists of two phases, a smooth inter-clump component and a clumpy component, and is characterised in terms of two parameters, namely the volume filling factor ff of the dense clumps and the density contrast C between the clump and inter-clump medium. The practical construction of the two-phase medium consists of randomly assigning a status (clump or inter-clump) to each dust cell in the dust medium. Typical values for the parameters C and ff vary widely in the literature. We use the values $C = 100$ and $ff = 0.1$ in this work, which are within the range of typical parameters used in other studies (e.g. Kuchinski et al. 1998; Witt & Gordon 2000; Bianchi et al. 2000b; Matthews & Wood 2001; Pierini et al. 2004; Doty et al. 2005).

In Figure 2.11, we show simulated images corresponding to the clumpy and smooth 3D models for the inner region of UGC 4754 at three different wavelengths (0.55 , 24 and $500\ \mu\text{m}$). It is important to note that the pixel-to-pixel variations in the images on the bottom row are not due to Poisson noise in the Monte Carlo routine, but represent real intensity variations due to the clumpy nature of the dust in the models. Figure 2.12 compares the total SED of the clumpy and smooth models. The relative differences are below 6% in the entire UV-mm domain. At UV wavelengths, the clumpy model

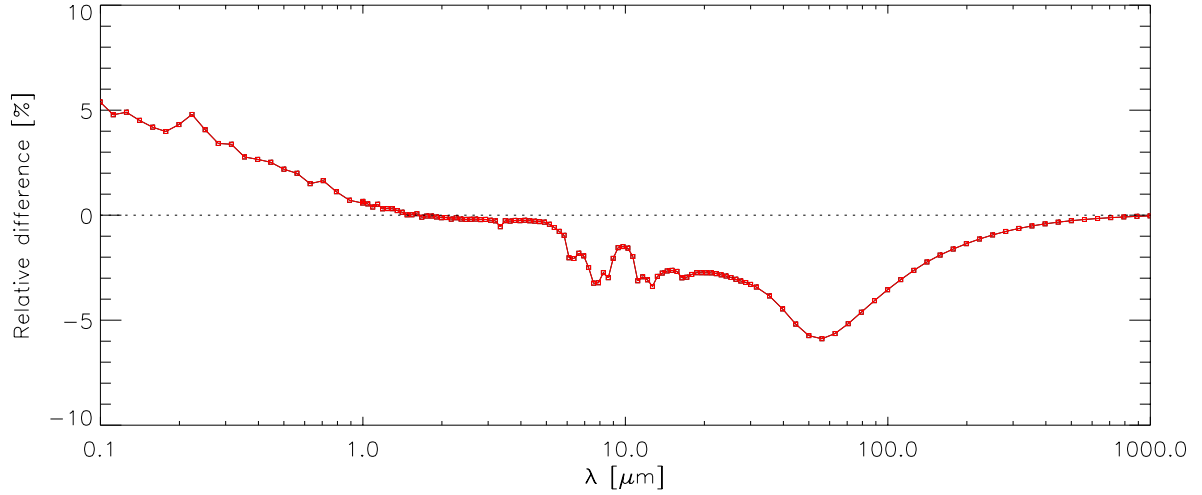


Figure 2.12: The relative difference $(F_{\lambda}^{\text{clumpy}} - F_{\lambda}^{\text{smooth}})/F_{\lambda}^{\text{smooth}}$ between the SEDs of clumpy and smooth 3D NLTE models for UGC 4754.

is slightly brighter than the smooth model, or put differently, slightly less UV radiation is absorbed by the dust. This is in agreement with conclusions found by other authors: for a fixed amount of dust, a clumpy dust medium absorbs radiation less efficiently than a smooth dust medium (e.g. Bianchi et al. 2000b; Pierini et al. 2004). When moving to longer wavelengths, the difference between the smooth and clumpy models decreases, as the fraction of absorbed versus unattenuated radiation decreases with increasing wavelength. At NIR wavelengths, there is virtually no difference anymore between the SEDs of the smooth and clumpy models. Moving to MIR and FIR wavelengths, we find that the clumpy model emits significantly less, particularly at wavelengths up to about 100 μm . This is no surprise, as the clumpy model was less efficient in absorbing UV and optical radiation. The result is that, for the same total mass, the dust in a clumpy model is on average both cooler and less luminous than the dust in a smooth model.

2.9

Concluding remarks on SKIRT

We have presented an updated version of the 3D Monte Carlo radiative transfer code SKIRT. The code uses various advanced optimisation techniques, both well-known and novel ones, that make the Monte Carlo process orders of magnitude more efficient than the most basic Monte Carlo technique. These techniques include an optimised combination of eternal forced scattering and continuous absorption, a multi-gaussian expansion technique and an efficient foam generator to generate random positions from the stellar density, and the use of peeling-off and smart detectors to create high signal-to-

noise images and SEDs.

The main novelty of the new SKIRT code is the possibility to calculate the dust temperature distribution and the associated infrared and sub-mm emission with a full incorporation of the emission of transiently heated grains and PAH molecules. To achieve this, we have chosen to link the SKIRT code to DustEM (Compiègne et al. 2011), a publicly available, state-of-the-art numerical tool designed to calculate the NLTE emission of arbitrary mixtures of dust grains. The advantages of this approach is that no LTE approximation is made, even for large grains, and that new physics (such as spinning dust emission or a temperature-dependent dust emissivity) can readily be included. We have implemented a library approach to limit the computational cost of the NLTE dust emission calculations inherent in DustEM. Our approach is inspired by the work by Juvela & Padoan (2003), but uses a slightly different approach that makes maximum use of all information in the simulation to calculate the dust emissivity and avoids the need for additional low-resolution simulations.

We have tested the accuracy of the SKIRT code, in particular of our NLTE library approach, through a set of simulations based on the edge-on spiral galaxy UGC 4754, previously modelled by Baes et al. (2010b). The models we ran were gradually refined from a smooth, 2D, LTE model to a fully 3D model that includes NLTE dust emission and a clumpy structure of the dusty ISM.

Using 2D models, we demonstrated the accuracy of our library approach: the relative differences in the SED between a model that uses the library approach and a model that uses brute force to calculate the dust emission are less than 0.2% at all wavelengths. Even for this 2D model with only 2500 dust cells, the difference in run time between both approaches are substantial; for 3D grids with several million dust cells the brute force approach becomes impossible. We have also explored the possibility to use a fixed set of precomputed dust emission templates instead of a dynamic library as the one we have chosen. While a template approach has the advantage that it is easier to implement and faster to run, we have demonstrated that it leads to significant deviations due to the fact that it does not take into account the shape of the interstellar radiation field. This highlights the need for a more advanced approach such as the library approach we propose.

We have subsequently applied the SKIRT code to calculate full-scale 3D NLTE models for UGC 4754. We found small differences ($< 2\%$) between 2D and 3D smooth models that are mainly due to differences in the vertical discretisation of the internal grid. Finally, we have compared 3D models with a smooth and a clumpy interstellar dust medium. We confirm the result found by other authors that, for a fixed amount of interstellar dust, a clumpy dust medium absorbs radiation less efficiently than a

smooth dust medium. As a direct consequence, the dust in clumpy models is on average both cooler and less luminous, and the observed infrared emission of clumpy models is less than the emission at these wavelengths of smooth models with the same dust mass.

Our simulations demonstrate that, given the appropriate use of optimisation techniques, it is possible to efficiently and accurately perform Monte Carlo radiative transfer simulations of arbitrary 3D structures of several million dust cells, including a full calculation of the NLTE emission by arbitrary dust mixtures. This significantly increases the number of applications where detailed radiative transfer modelling can be used. For example, we have started an investigation of the energy balance crisis in a set of edge-on spiral galaxies: our intention is to fit detailed radiative transfer models to UV/optical/NIR images for a set of edge-on spiral galaxies, predict the resulting MIR/FIR/sub-mm emission and compare these predictions with the available long wavelength data. Many other applications (AGNs, circumstellar discs, merging galaxies,...) are possible, and the authors welcome all projects that can make use of SKIRT.

A new era of far infrared astronomy: the *Herschel Space Observatory*

3

The following describes the *Herschel Space Observatory* (Section 3.1), and more specifically its instrument PACS (Section 3.2), summarising information taken from the *Herschel* Observers' Manual¹ (mainly Chapters 1–3) and the PACS² (Chapters 1–3 & 5) and SPIRE PACS Parallel Mode³ Observers' Manuals most relevant to the observing programmes presented in the next Chapters. The standard pipeline (PACS Data Reduction Guide for Photometry⁴, Chapters 3–4) is discussed in Section 3.3, along with some modifications devised precisely for the data reduction of these programmes. Finally, a number of map-making algorithms (PACS Data Reduction Guide, Chapters 4–5) are investigated in Section 3.4, comparing their practicality, efficiency, the usefulness of their results, as well as their applicability to specific scientific objectives, and a few remaining problems are mentioned (Section 3.4.4).

While the tools, programmes and pipelines discussed in this Chapter are provided by the *Herschel* Science Centre, the dedicated instrument teams or third-party external developers, it is important to understand that even today, 4 years post-launch, there is no standard pipeline which returns optimal results for all possible cases. This is rather obvious, since many steps are dependent on the observing mode and on the target. It is no wonder that at almost every step of the way, we had to test different options within the pipeline, only to find some quite unexpected results in the final maps. Due to the unique nature of the HeViCS observations (discussed in further detail in the next Chapter), going to an unrivalled depth for its very large field size, we provided some valuable feedback to the instrument teams and developers about issues even they had no previous experience with. We would also like to stress that the two-step approach discussed in Section 3.4.1, processing a first-pass map to use as input for generating the final map in a second pass, was developed by us, jointly with the people responsible for the PACS data reduction in H-ATLAS, another team processing large-field observations.

¹ <http://herschel.esac.esa.int/Docs/Herschel/pdf/observatory.pdf>

² http://herschel.esac.esa.int/Docs/PACS/pdf/pacs_om.pdf

³ http://herschel.esac.esa.int/Docs/PMODE/pdf/parallel_om.pdf

⁴ http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/pacs_phot.pdf

At the moment of its launch, the *Herschel Space Observatory* had undergone nearly three decades of development and research into its feasibility (Pilbratt et al. 2010). When the European Space Agency (ESA) made a call for mission proposals in July 1982, the Far InfraRed and Submillimetre Space Telescope (FIRST) was formally suggested later that year. It was eventually included as a cornerstone mission of ESA's long-term Horizon 2000 plan (Longdon 1984). After various mission design studies, it was approved by the ESA Science Programme Committee (SPC) in 1993 as an Earth orbiting spacecraft with a passively cooled 3 m telescope and two mechanically cooled instruments. Using the lessons learned from the *Infrared Space Observatory* (ISO, Kessler et al. 1996), a switch to a helium cooled cryostat and to an orbit around the second Lagrangian point (L2) of the Sun-Earth system was incorporated. Eventually, three instruments were approved in 1999 and construction of the spacecraft began in 2001. In the meantime, FIRST had been renamed *Herschel* in 2000 in honour of William Herschel's discovery of infrared light exactly 200 years earlier (Herschel 1800).

The main scientific objective of the *Herschel Space Observatory* is to observe the cool universe: the *Herschel* wavelength range corresponds to celestial bodies at temperatures of a few to a few tens Kelvin emitting continuum radiation, to the brightest emission lines from atomic and molecular gases at temperatures up to a few hundreds K, and to the bulk of the (modified) black-body radiation by small dust grains. The latter absorb a significant part of the radiation at shorter wavelengths (UV, optical and NIR) and re-emit the acquired energy mainly at the longer wavelengths *Herschel* observes. The intended objects of study vary from solar system objects, over star formation regions in our Galaxy and its interaction with the interstellar medium, and the ISM and star formation in nearby galaxies and at higher redshift, to AGNs and even cosmological studies. Because *Herschel* covers a previously largely unexplored wavelength range and due to its excellent photometric and spectroscopic capabilities, it had a clear potential for new sources as well explanations for known sources from the start, for instance through large unbiased photometric surveys and spectroscopic follow-ups.

Of the approximately 20000 hours available for scientific observations, about 32% have been designated Guaranteed Time (GT) and are assigned to the teams responsible for the development of *Herschel* and its instruments. The remaining Open Time (OT) is available to the scientific community in general, and is allocated by the *Herschel* Observing Time Allocation Committee (HOTAC) on the basis of the merit of the submitted proposals. Observation time was basically allotted during 3 calls, each first opened for GT holders and only afterwards for OT proposals. To fill *Herschel*'s observing schedule

for roughly the first year of routine operations and due to the lack of an all sky survey for its wavelength range, the first call was dedicated to Key Projects or Key Programmes (KP), which mainly cover large spatial and spectral surveys (Pilbratt 2008; Pilbratt et al. 2010). The GT and OT parts for this call were each awarded over 5000 hours of observation time. The next 2, inflight Announcement of Opportunity (AO) calls occurred at roughly one and two years after launch, respectively, to allocate the remainder of the available time.

The *Herschel Space Observatory*, as an observatory, consists of two main parts: the ground segment, and the spacecraft itself. The former is subdivided into a few separate centres:

- The Mission Operations Centre (MOC) in Darmstadt, Germany, which handles the day to day operations of the spacecraft, monitoring its status and transmitting commands to the spacecraft (such as for observations or orbital station-keeping) as well as receiving back the data and telemetry from it through one of ESA's ground stations.
- The *Herschel* Science Centre (HSC) near Madrid, Spain, which provides the main support to the scientific community, such as proposal calls, observation planning, automatic pipeline processing of observational data and subsequent quality control, data archival and providing information and support concerning all these activities.
- The NASA *Herschel* Science Center (NHSC) in Pasadena, California, which carries out similar support for scientific users of *Herschel* based in the US.
- The Instrument Control Centres (ICC) for the individual instruments, which are responsible for their respective instruments, providing various observing modes, as well as tools for processing the data, and carrying out the occasional calibration observation.

The *Herschel* spacecraft, weighing in at 3400 kg just before launch and measuring 7.4 m in height and 4.0 m in width (Figure 3.1), has a modular design: a sunshield, a service module (SVM), a payload module (PLM) and the telescope structure on top of the latter are all joined together to form the space observatory. The sunshield has two main functions: supplying power to the spacecraft through its solar array directed towards the Sun and shielding the rest of the spacecraft from the sun, thereby providing passive cooling.

The SVM contains the electronics to control the spacecraft and the individual instruments, as well as power, communications, attitude and orbit control facilities. It also carries out the onboard data handling. Since this part of the spacecraft has a relatively

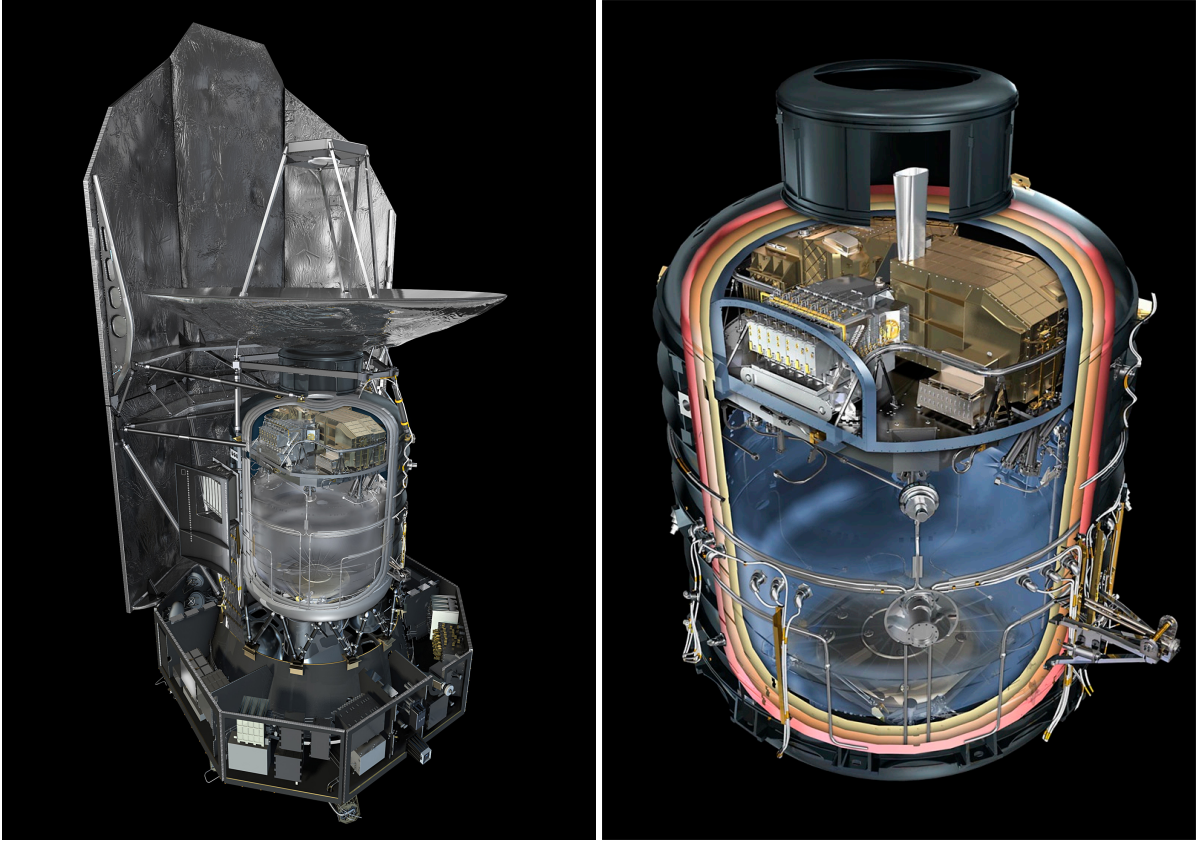


Figure 3.1: *Left:* Overall view of the *Herschel* spacecraft, showing the sunshield at the back, the telescope at the top, the service module at the bottom and the payload module in between, with a partial cutaway of the latter, revealing its inside structure. *Right:* A cutaway through the cryostat of the payload module, displaying the helium tank at the bottom and the optical bench with the three instruments on top of it, both enclosed by three layers of vapour-cooled shields. Images: ESA.

warm, controlled ambient temperature, a thermal shield provides isolation between the SVM and the PLM.

The design requirements for the *Herschel* telescope (Doyle et al. 2009) were for it to be as large as possible without having to deploy movable parts after launch, as cold as possible with only passive cooling available, a total wavefront error (WFE) smaller than $6 \mu\text{m}$ at the focal plane and able to sustain both the varying mechanical and thermal conditions during its lifetime, all under the additional condition that it must weigh as little as possible. The optical design of choice meeting these demands is a classical Cassegrain with a primary mirror diameter of 3.5 m and an undersized secondary, limiting the effective diameter of the primary to 3.28 m. Using silicon carbide (SiC) as the material to construct the telescope with, turned out to be the most cost effective option to build a telescope of this size meeting all the requirements (Sein et al. 2003). The primary mirror was made out of 12 separate petals, each of them among the largest

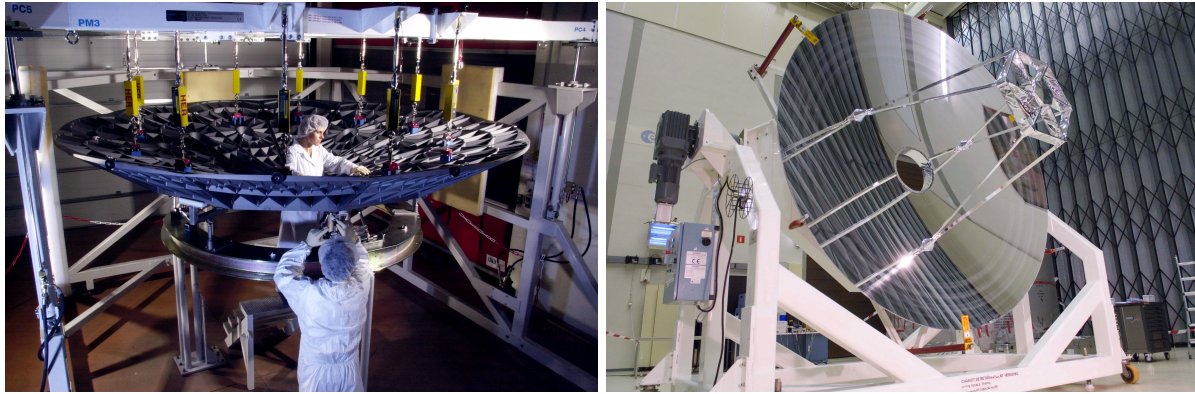


Figure 3.2: Left: The *Herschel* primary mirror after its 12 segments have been sintered and brazed together. Right: The completed telescope structure ready to undergo testing activities. Photos: EADS Astrium/ESA.

SiC monolithic objects ever manufactured at the time, which were sintered and then brazed together to form a single structure, which in turn was machined and polished to meet the required measurements and accuracy, while the secondary was made in one piece and underwent the same treatment as the joined primary. Both mirrors were then coated with an aluminium layer for high reflectivity and low emissivity, and a protective plasil (silicon oxide) layer. The secondary is suspended above the primary at the correct position using a hexapod structure, which is bolted to the primary with 3 fittings (Figure 3.2). The whole structure has a passive design, which means it has no focussing capabilities, and the alignment and performance were tested under cold conditions to be within the requirements, while its total weight is no more than 320 kg, which is about a third of the *Hubble Space Telescope*'s 2.4 m primary mirror. During cooling down of the spacecraft, the telescope was kept warm with heaters to prevent it acting as a cold trap where gases vented during the early stages of the mission could condense, until it was allowed to cool down as well to its operational temperature around 85 K.

The PLM consists mainly of the cryostat vacuum vessel (CVV), containing the superfluid helium tank and the optical bench supporting the three focal plane unit (FPU) instruments, both surrounded by three successive layers of vapour-cooled shields within the CVV. The helium tank has a volume of 2367 litres to support inflight cooling of the instruments at their required temperatures over a mission lifetime of 3.5 to 4 years. Cooling of the instrument detectors is achieved through thermal connection to both the tank's liquid helium, and the circulating evaporated cold gas at various temperatures as it is carried around within the CVV through pipes until it passes the three vapour-cooled shields and is vented into space.

The three scientific instruments together cover the FIR and sub-mm spectral range 55–

671 μm and offer both photometry and spectroscopy observing capabilities, using various mapping modes. These instruments are:

- the Photodetector Array Camera and Spectrometer (PACS)
- the Spectral and Photometric Imaging REceiver (SPIRE)
- the Heterodyne Instrument for the Far Infrared (HIFI)

The PACS instrument houses an imaging photometer ($\sim 3.5' \times 1.75'$ field of view) as well as an integral field spectrometer ($47'' \times 47''$ field of view), both observing in the wavelength range 60–210 μm and will be discussed into detail in the next Section, while the SPIRE instrument provides both broad band photometric imaging in three bands centred at 250, 350 and 500 μm over a $4' \times 8'$ field of view and imaging spectroscopy over the range 194–671 μm covering a circular field of view of $2'$. The HIFI instrument offers high resolution spectroscopy for a single diffraction-limited beam in the ranges 157–212 μm and 240–625 μm .

On 14 May 2009, *Herschel* was launched together with *Planck* from Kourou, French Guiana, using an Ariane 5 ECA. Both were injected onto a trajectory that would take them to a different Lissajous orbit around the second Lagrangian point L2 of the Sun-Earth system (Figure 3.3). For *Herschel*, this means its distance to Earth varies between 1.2 and 1.8 million km. This choice of orbit has the advantage that both the Earth and the Sun are located close to each other on the sky from the perspective of the spacecraft, leaving a relatively large area of sky available for observation, since pointing the telescope should avoid both celestial bodies, with an aspect angle of at least about 120° between the Sun and the optical axis. In an earlier design phase of the mission, *Herschel* would revolve around Earth on a highly elliptical, near-geosynchronous orbit, but this would limit observation time to whenever the spacecraft is outside the Earth's radiation belts. Going for the L2 option meant that the *Herschel Space Observatory* would remain well outside the detrimental influence of these radiation belts. However, this choice has one major drawback: since there are currently no commercial applications for L2, there has never been any real incentive to develop high throughput communication links to spacecraft located there, limiting the data transfer between *Herschel* and the MOC to 130 kbps, which in turn puts further restrictions on the data acquisition by the instruments.

Right after the separation from the launcher, the Low Earth Orbit Phase (LEOP) commenced, checking out the status of various sub-systems on the spacecraft, but not yet of the instruments. These were turned on a short while later, during the Commissioning Phase (CoP), which lasted about two months. This also involved opening the cryo-cover one month after launch, which exposed the instruments to the sky for the

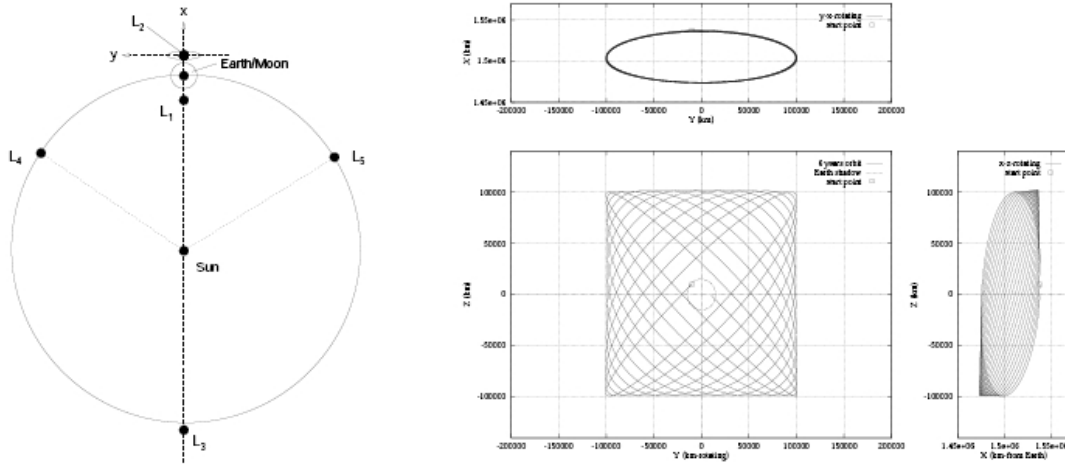


Figure 3.3: *Left:* Diagram of the Lagrangian points in the Sun-Earth system, with the z -axis normal to the shown plane. *Right:* Projection of a Lissajous orbit around L_2 onto three perpendicular planes through the axes. Images: *Herschel* Observers' Manual.

first time. The spacecraft was thermally stabilised by the time the Performance Verification Phase (PVP) started, which was designed to check out and characterise all sorts of calibration parameters of the instruments, verifying that they were performing within design requirements, as well as validating the various observing modes and the associated calibration and data processing. The transition into the Science Demonstration Phase (SDP) progressed gradually, with PVP and SDP activities alternating, until those for the PVP were no longer necessary. The SDP was used for specific observations from the approved Key Programmes, to test both *Herschel's* capabilities and various observation strategies. The change into the Routine Science Phase (RSP) was also very gradual, and by the end of 2009 most observations were designated RSP. One exception was made for the HIFI instrument, which sustained a failure on 2 August 2009 in its warm electronics due to a radiation impact. The instrument was reactivated on 10 January 2010 using auxiliary systems and followed the successive phases on a different time schedule, in parallel to the PACS and SPIRE instruments, which were ahead in the phases, and made up the lost ground by the end of April 2010, using a dedicated HIFI Priority Science Programme (PSP) as a replacement for its SDP. The contents of the helium tank is projected to last into the first months of 2013, but when boil off occurs, the RSP has effectively ended, since *Herschel's* instruments need to be cooled to below 10 K to operate in a scientifically meaningful way and therefore it has no warm phase. At this point, a consolidation of all data will commence, preparing it for historical archiving, allowing continuous exploitation of *Herschel* data.

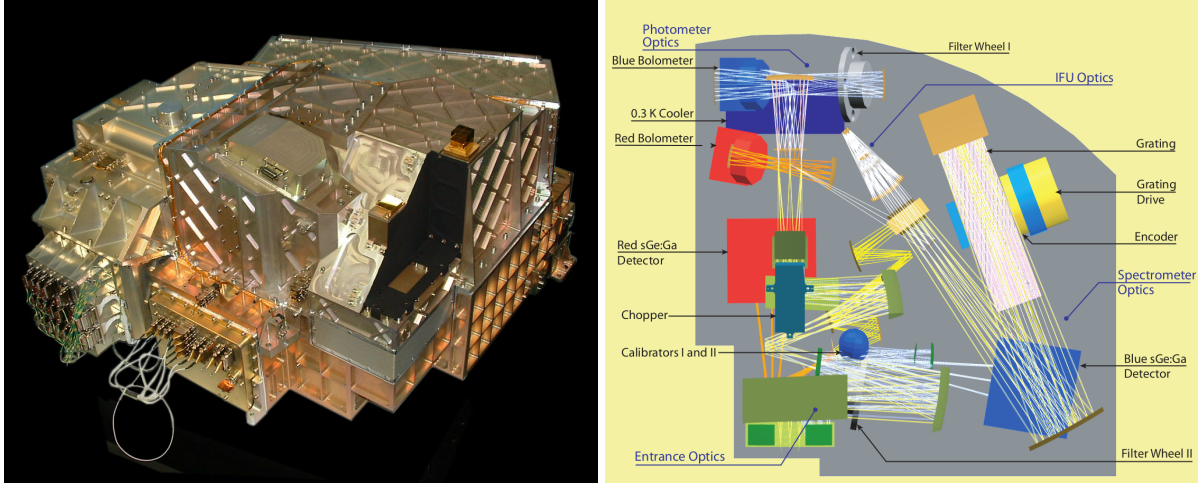


Figure 3.4: *Left:* The PACS instrument. *Right:* Schematic of the different ray paths inside the instrument towards the various detectors (Poglitsch et al. 2010).

3.2 PACS instrument: Photodetector Array Camera & Spectrometer

The PACS instrument (Poglitsch et al. 2010) onboard *Herschel* contains both an imaging photometer and an integral field spectrometer, both covering the wavelength range 60–210 μm . An image as well as a schematic of the instrument are shown in Figure 3.4.

The spectrometer uses two 16×25 pixels Ge:Ga photoconductor arrays (stressed and unstressed), covering a $47'' \times 47''$ field of view onto 5×5 spatial pixels. These pixels are rearranged by an image slicer to project them onto the photoconductor arrays' 25 modules of 16 pixels each, where each module records the spectrum of its respective spatial pixel using its 16 pixels for the spectral dimension. Using a 1×25 pixels entrance long slit for the grating spectrometer, both arrays offer a spectral resolving power range $R = 1000\text{--}4000$, depending on the wavelength.

The photometer offers both a long wave (“red”) and a short wave (“blue”) bolometer array, each having a $\sim 3.5' \times 1.75'$ field of view, which both observe at the same time, due to a dichroic beamsplitter. Using a filter wheel, the blue bolometer can observe in either a “blue” (shortest waves: 60–85 μm) or “green” (longer waves: 85–130 μm) channel, while the red bolometer covers the 130–210 μm wavelength range (Figure 3.5). Both blue and red bolometers use monolithic 16×16 square pixels filled sub-arrays, tiled together to form their respective focal plane arrays: in the case of the blue bolometer 4×2 of these sub-arrays, while the red has 2×1 of them. This results in a total of 64×32 (blue) and 32×16 (red) pixels, with each of those pixels covering $3.2'' \times 3.2''$ and $6.4'' \times 6.4''$ of sky area, respectively. The small gaps between sub-arrays have to be covered by the used mapping methods.

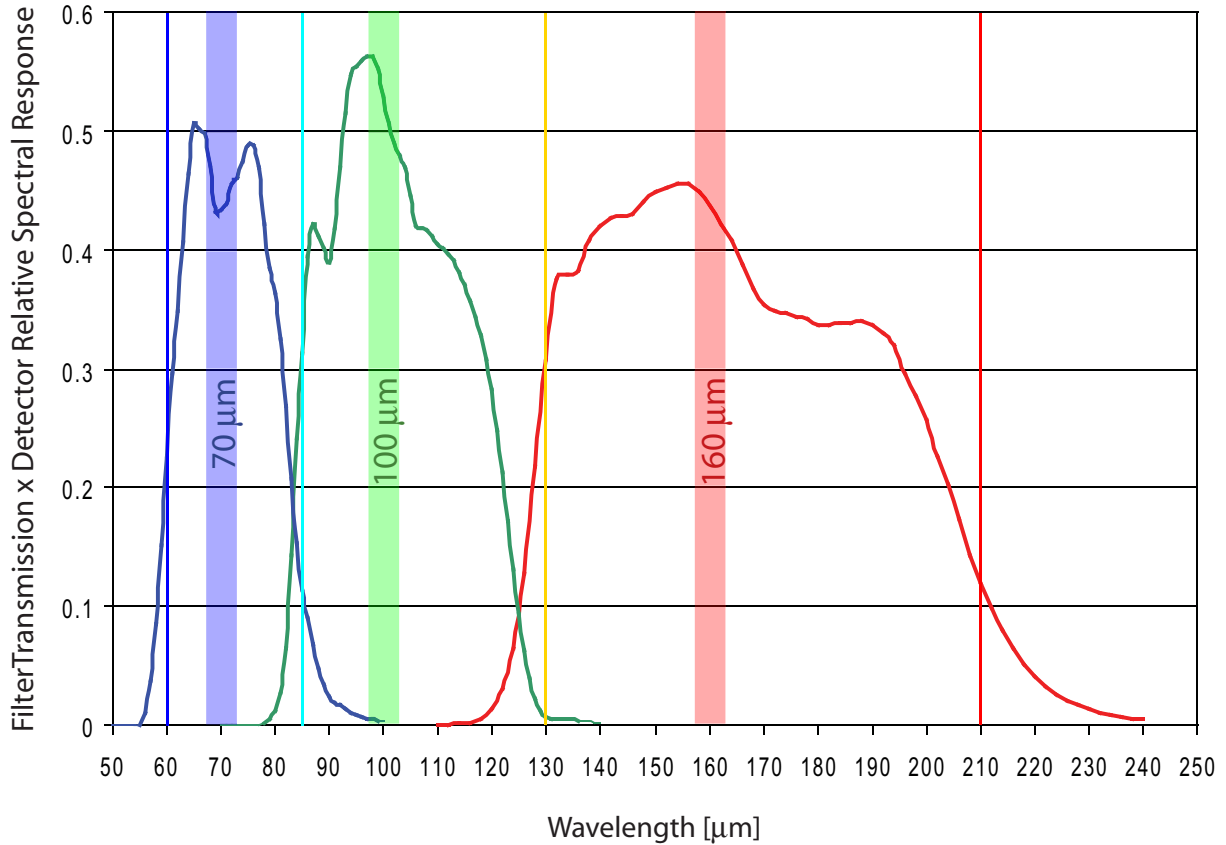


Figure 3.5: Effective spectral response for the three available PACS passbands (“blue”, “green” and “red”) (Poglitsch et al. 2010).

While the PACS instrument as a whole is cooled to the satellite-provided “Level 1” temperature range of 3–5 K, the bolometer structures are kept at the lower “Level 0” cryostat temperature of about 1.65 K. The sub-arrays are thermally isolated from their surroundings and are cooled down further to 0.3 K using a dedicated closed cycle ^3He sorption cooler. The latter can provide cooling to the continuous operation of the bolometers for a design hold time of two days, but inflight measurements have determined the cooler performance is significantly better than required. After this hold time, the cooler contents have to be recycled, usually during the daily communications.

All PACS photometric observations gather data from both the red and the blue bolometer, using either the blue or the green filter for the latter, depending on the observer’s request. Three different types of observing modes or Astronomical Observing Templates (AOTs) involving the photometer side of the PACS instrument have passed inflight validation. The first is the chop-nod technique, which is used for point sources, and is achieved through movements of the chopper, a moveable mirror within the PACS instrument, and nodding of the spacecraft as a whole, perpendicular to the direction

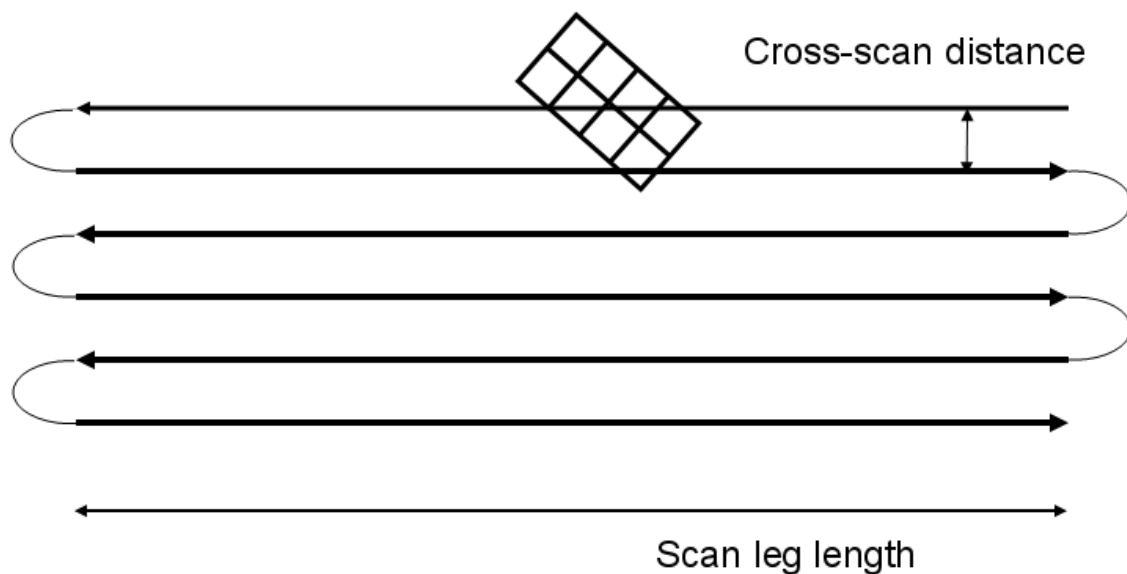


Figure 3.6: Schematic view of scan map, in which two consecutive scan legs are performed in opposite directions. In between, the spacecraft decelerates, moves to the next scan leg and accelerates again to the nominal scan speed for the observation (PACS Observers' Manual & Poglitsch et al. 2010).

of the chopping. The other two involve the scan technique, which is mainly used for large area surveys, but can also applied to small fields and point sources: scan maps in either PACS prime mode or PACS/SPIRE parallel mode. The former only uses the PACS photometer, while the latter makes concurrent observations of the sky with the SPIRE photometer.

The scan map technique (Figure 3.6) is achieved by slewing the satellite at a consistent speed along great circle arcs on the sky, which are practically parallel to each other, given the restrictions on the length of the individual scan legs. The scan speeds available for the PACS prime mode are $10''$, $20''$ or $60''/s$, while for the PACS/SPIRE parallel mode, the slowest of these speeds was dropped. When a specific scan leg is finished, the spacecraft decelerates, moves itself to a point, located a specific cross-scan step distance from the finished scan leg, and accelerates again to the scan speed for that observation, to observe the next scan leg in the opposite direction. Due to these scanning movements, the point spread function (PSF) is elongated along the scan direction, especially at the fastest scan speed. It is recommended to combine two observations of the same field using different scan directions, preferably (nearly) orthogonal to each other, to remove the striping caused by $1/f$ noise.

In PACS prime mode, the observer can specify the number of scan legs, their length, the separation between them, the scan speed, the orientation angle of the detector ar-

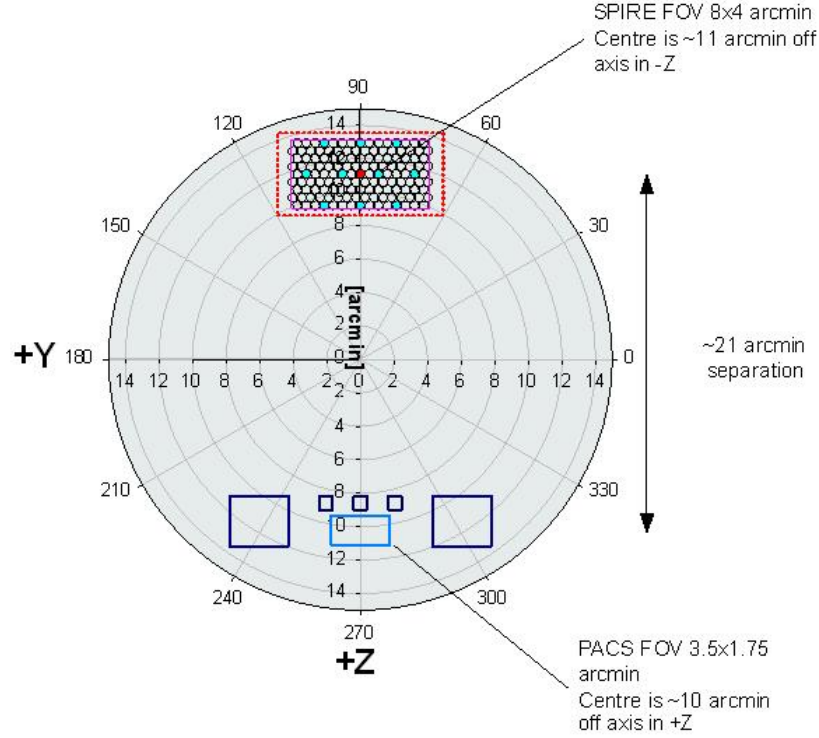


Figure 3.7: The *Herschel* focal plane layout with the positions of the PACS and SPIRE fields of view. Image: SPIRE PACS Parallel Mode Observers' Manual.

rays with respect to the scan direction and the number of times this scan map has to be repeated, all provided the maximum time allowed for a single observation is not exceeded. In PACS/SPIRE parallel mode however, only the scan speed and the height and length of the area to be covered by both instruments can be given. The orientation angle is fixed to $\pm 42.4^\circ$, the 'magical' angle for SPIRE observations, ensuring the SPIRE data has a uniform coverage of the area (Sibthorpe et al. 2006; Waskett et al. 2007). As a consequence of this orientation angle and the offset of $\sim 21'$ between the PACS and SPIRE focal planes (Figure 3.7), the separation between legs and therefore also the total number of legs is determined automatically as well to provide more or less homogeneous coverage for both instruments.

For all PACS photometric observations, the bolometers have a read-out frequency of 40 Hz. However, given the limited data transfer bandwidth between the spacecraft and the ground stations from L2, the effective data sampling rate is reduced to 10 Hz by averaging each set of 4 consecutive data frames before transmission. In PACS/SPIRE parallel mode, the blue bolometer data is even further cut by half, taking the average of 8 instead of 4 successive frames, resulting in a final sampling frequency of 5 Hz. Another applied compression mechanism depends on the gain setting: low gain observations, used for especially bright sources, are unaffected, but for high gain PACS

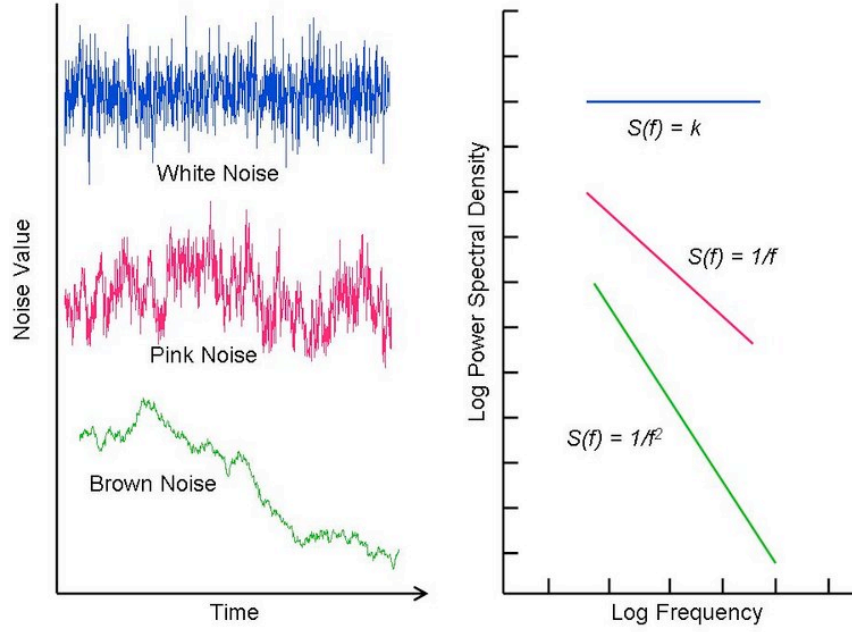


Figure 3.8: A comparison of the temporal behaviour (*left*) and power spectrum (*right*) for different types of noise, exemplifying the $1/f$ or “pink” noise relevant to PACS data (Popesso et al. 2012).

prime and PACS/SPIRE parallel mode observations, the last 1, respectively 2, bits of all averaged signal values are rounded off.

Nearly all electronic components and devices show a flicker noise or $1/f$ noise behaviour (Figure 3.8), and the PACS bolometer arrays, their data multiplexers and read-out electronics are no exceptions. The designation as $1/f$ noise is quite loose, as it is used more generally to refer to any noise of the form $1/f^\alpha$ with f the frequency and $0 < \alpha < 2$. In the case of the PACS photometers, α actually has a value close to $\frac{1}{2}$. The underlying source for this noise is a rather slowly fluctuating process, such as varying defects in metals or charge traps being occupied or not in semiconductors (Weissman 1988). The spectral density of this noise component dominates the sky signal for pointed observations, but it can be mitigated by spatially modulating the signal, such as by chopping/nodding or scan mapping, which allows for an easier removal of the $1/f$ noise during the data reduction.

Both the spectrometer and the photometer share two calibration sources, radiating uniformly as modified black-body sources just above and below the telescope background. The requirement during the SDP of roughly one calibration block per hour for longer observations, each occurring during the turn-around between scan legs, was relaxed to just one calibration measurement at the beginning of the observation, during the slew time towards the target.

3.3 PACS photometer DR: preprocessing to calibrated scientific level

Once the observational data has been transferred back to Earth through the down-link, it is automatically processed at the HSC with the appropriate standard pipeline for the relevant type of observation. Conceptually, this pipeline is usually divided in two parts, with the first one responsible for transforming the raw engineering data, denoted as Level 0 (L0), into data cubes which are calibrated, indicated with Level 1 (L1). The second part then handles the further reduction to produce scientifically usable imaging maps or spectrometric data cubes, marked as Level 2 (L2). Although this standard pipeline usually delivers quite decent results, for most cases it is advised to manually run the pipeline again within the *Herschel* Interactive Processing Environment (HIPE, Ott 2010), using customised settings for the specific observations carried out. The pipeline itself is written in Jython, an implementation of the Python language using the Java programming language. Most tasks within the pipeline have actually been implemented in Java for optimal performance.

3.3.1 The standard pipeline

What follows, is a general overview of the standard pipeline for scan map observations, which is delivered together with HIPE and is also used for the automatic data reduction. The HSC hosts the observational data through the *Herschel* Science Archive (HSA), which allows downloading any combination of the components the observational context for a specific observation consists of: the raw data L0, the results of the standard pipeline L1 and L2 as well as an intermediate Level 0.5, the auxiliary data such as pointing and housekeeping data, and the calibration files.

The first task of the standard pipeline, `getObservation`, loads all these data into the session, through either an open connection to the HSA or a locally saved copy of the data. The next step is then to extract the actual scientific signal from it, referred to as the timeline frames, or frames for short, as well as the pointing, photometer housekeeping and orbit ephemeris products, which contain the telemetry and various status measurements. The final setup step is the retrieval of the calibration files with the `getCalTree` task.

The next few tasks involve the identification of the various types of data blocks within the observation with `findBlocks`, distinguishing the calibration blocks from the actual scientific data using `detectCalibrationBlock` and finally removing those calibration blocks with `removeCalBlocks`.

The following step is to flag various pixels as useless for further scientific processing:

pixels that were determined to be corrupt in tests on the ground, using the `photFlag-BadPixels`, while `photFlagSaturation` flags those pixels which, depending on the bias used for the observation, have saturated. Both tasks create and populate their respective masks for the timeline frames. The loss rate of bolometer pixels due to these two tasks is only a few percent, so the influence on the total coverage is negligible. It should be pointed out that an additional `photMaskCrosstalk` task is present to mask crosstalk effects, but generally not applied. The bolometer pixels are sequentially read out column by column through the multiplexer, using the same read-out electronics, and as a consequence, a phenomenon denoted as crosstalk can occur. Since the read-out electronics are common to all columns, the signal from a specific pixel can be modified by the signal from the corresponding pixel of the previously read column. This is normally not noticeable, except for pixels following a dead pixel, or for all pixels from the first column, which are thus influenced by the last column as the multiplexer cycles back to the beginning of the bolometer array and can therefore produce an appreciable effect in the final map. In reality, mainly the red bolometer is affected by this crosstalk phenomenon.

The next tasks are responsible for unit conversions: `photConvDigit2Volts` takes the digitised values of the bolometer signals and substitutes them with the corresponding physical values in Volts, while `convertChopper2Angle` converts the chopper angle values from digital into physical units, in this case degrees. At this point, the data is considered to have reached Level 0.5, meaning they have been partially reduced with corrections for instrumental effects, without user interaction, and the data reduction pipelines of the different PACS photometric observations have all the steps up to this point in common. While some of the following tasks are shared between different types of observations, most of them are specific to scan map observations.

The subsequent step uses the pointing and orbit ephemeris products to add the astrometric coordinates calibration: first the `photAddInstantPointing` task for a reference pixel corresponding to the bolometer centre, and then the `photAssignRaDec` task for each individual pixel of the bolometer arrays.

Then there are two final actions to be performed in order to fully reduce the data to Level 1 calibrated data cubes with correct pointing data and masks. With `photRespFlatfieldCorrection`, the varying pixel sensitivities and optical paths are corrected for on the one hand and the measured signal is converted from Volts into Jansky per pixel on the other hand. Finally the deglitching is responsible for detecting and masking the incidence of cosmic rays on the detector. The latter task will be discussed in more detail later in this Section. To go from L1 to L2, these reduced timeline data have to be processed into maps, with the various options available covered in the next Section.

3.3.2 Removal of calibration blocks

As previously mentioned, one of the first tasks in the standard pipeline is the removal of the calibration blocks taken during each observation. This is especially important for longer observations taken during the Science Demonstration Phase, since these contain one calibration block for roughly each hour of observation. During these blocks, the detectors are illuminated by a calibration source instead of the sky by “chopping” a mirror along the light path within the instrument. These calibrations were carried out right before the start of the observation, and then each hour when the telescope turned around between scan legs, in order not to affect the target area. From the SDP results, it was concluded that the detectors were sufficiently stable, and for the Routine Science Phase the number of calibration blocks per observation was reduced to just the one at the beginning.

Proper removal of these calibration blocks is still of considerable importance, because following the calibration flashes, the array pixel signals need some time to relax back to more or less nominal values. This was particularly problematic in early versions of the standard pipeline, since the standard task failed to remove part of the calibration block frames (Figure 3.9). To rectify this situation, we had to explicitly check the chopper angle as well as other status parameters to determine the frame indices of the remaining calibration block frames and then remove them. However, this problem was resolved in more recent versions of the pipeline.

3.3.3 Deglitching

At infrequent intervals, the PACS detector arrays are hit by cosmic ray particles or secondary particles from their interaction with other parts of the satellite. These then cause a usually sharp peak in the timeline signal of the affected pixel or pixels. Those peaks are termed glitches and three different kinds of them have been found for the PACS photometer (Figure 3.10, Billot et al. 2010):

- A positive glitch (left panel in Figure 3.10) occurs when the particle causing it hits one of the bolometer pixels of the array. This type happens most often at $\sim 85\%$ of all events, and the particle deposits much more energy than the average FIR photon carries, causing a sharp rise of the bolometer temperature and therefore also the corresponding signal. Several readouts are necessary before all this energy is dissipated and the bolometer attains its equilibrium.
- Most of the remaining $\sim 15\%$ of hits involve negative glitches (middle panel), which are induced by particles hitting the walls between the pixels. Because the bolometer temperatures are measured relative to temperature of these walls, this

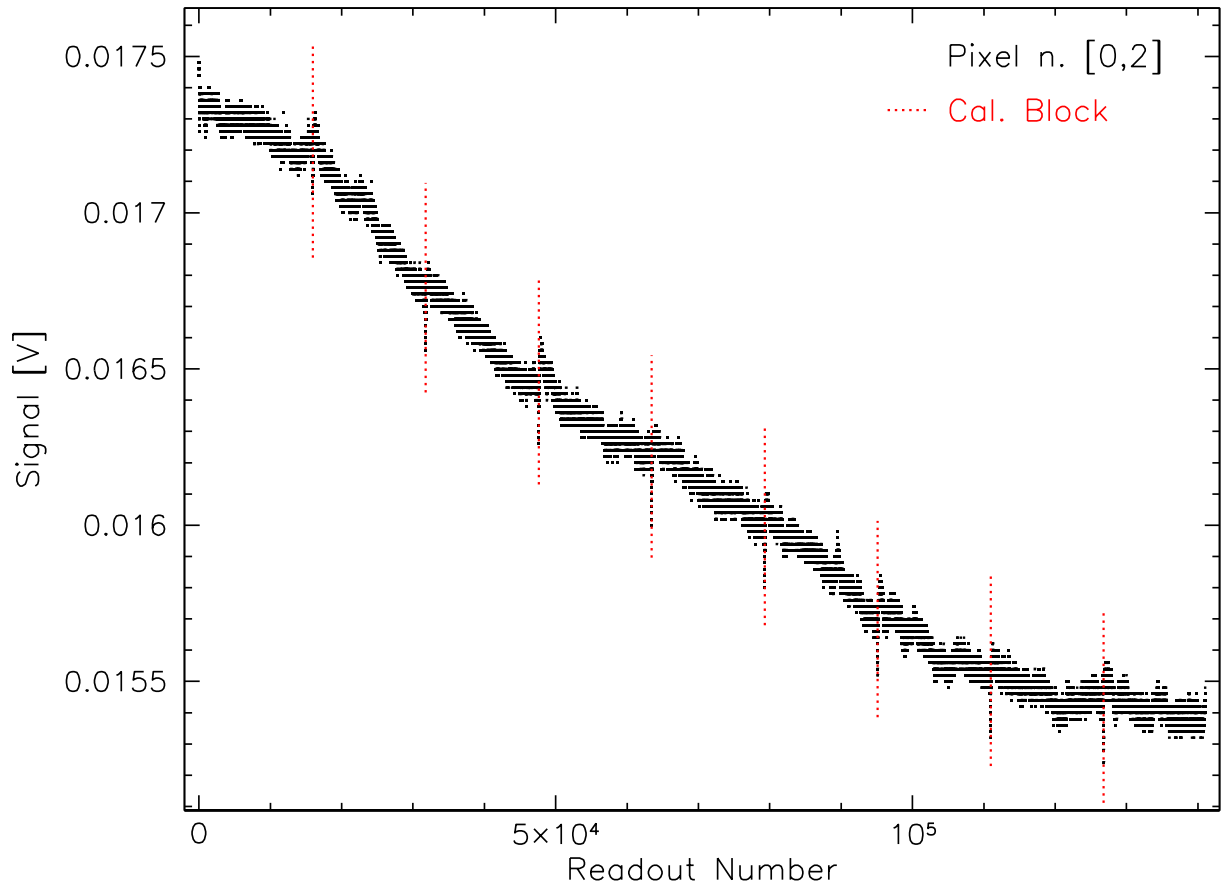


Figure 3.9: Calibration blocks (indicated with red lines) can badly affect the timeline of a detector pixel if not properly removed, causing large jumps in the signal levels.

specific kind of hit causes a negative dip in the signal of the surrounding pixels. Due to the bulky nature of the walls compared to the bolometer pixels as well as their larger heat capacity, the signal magnitude of these glitches is much smaller and the proper state is restored faster.

- A very rare type of glitch appears when some part of the readout electronics is hit (right panel). This event has a very low frequency, because the affected transistors have a very small cross-section, but its impact is still quite dramatic with respect to the data reduction: in most cases, an entire sub-array column of pixels, which share common buffer electronics, shows the same signal behaviour of a sudden offset jump, after which the signal for the different pixels appears to maintain a similar trend as before the jump. Although this seems to be a discontinuity in the signal, it is in fact a glitch with a very slow relaxation.

The total average occurrence rate of all these glitches is predicted to be about 5 particle hits per second per 16×16 pixel sub-array, and dedicated measurement campaigns are in fairly good agreement with this, depending on the glitch detection method used (Billot et al. 2010). The overall impact of glitches is rather small, since the affected

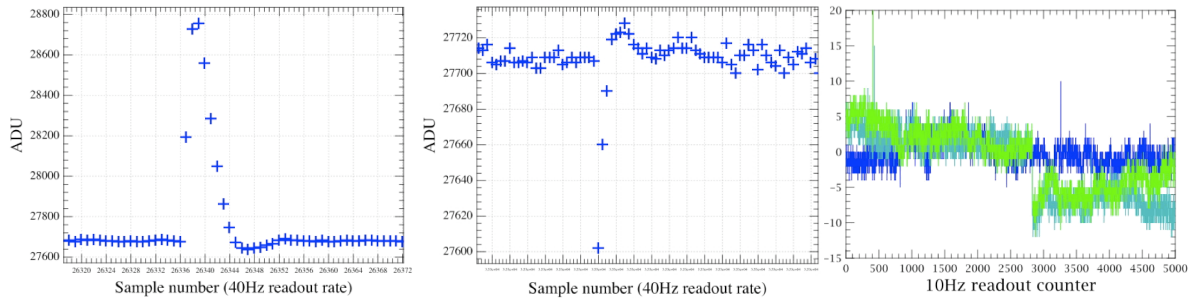


Figure 3.10: The various types of observed glitches, caused when different impact areas are affected by cosmic ray particles or their secondaries: *Left:* Positive glitch, pixel hit. *Middle:* Negative glitch, wall hit. *Right:* Signal jump (green timeline), readout electronics hit (Billot et al. 2010).

amount of the PACS photometer data is less than 1% of the total.

Generally, two different approaches are available within HIPE for deglitching the PACS data, with algorithms using either the temporal or the spatial information contained in the signal data. The former algorithms perform an analysis of the timelines for the various detector array pixels to locate glitches in each of them, while the latter involve a projection on sky pixels to identify outliers in the sky signal for each of them as glitches. As examples for both approaches, the algorithms used most often, MMT deglitching, based on the multiresolution median transform (MMT), and second level deglitching will be discussed, representing the temporal and spatial algorithms respectively.

MMT Deglitching

This kind of deglitching can be invoked within HIPE using the `photMMTDeglitching` task and it can be applied before the astrometric calibration, since the redundancy in sky coverage is not used. Instead, the timeline for each detector pixel is scanned for the different frequencies in the signal, correcting it for each occurrence of frequencies associated with glitches. This analysis is achieved through the multiresolution median transform algorithm outlined in Starck et al. (1995, 1996); Starck & Murtagh (1998) and Starck et al. (1999), which basically performs a sequence of median transforms of an input image through square kernels of increasing pixel size. By comparing the results at different resolution scales, the information content of the image at these different scales is determined, using an estimate of the noise characteristics.

Crucially, this method still identifies both glitches and real sources in the same way, therefore it requires some form of pattern recognition to separate them, on top of a guess about the noise behaviour. This pattern recognition in turn should be based on a good characterisation of the detector behaviour after it is hit by a cosmic ray and the consequential glitch in the signal timeline, but in the absence of this knowledge for the

PACS detectors, the user is restricted to a proper choice of the maximum resolution scale, giving the limit up to which the median transforms are determined, and of the standard deviation, acting as a threshold for glitches.

It is impossible to find an optimal combination of these parameters applicable to all different kinds of observations. If these settings are kept too relaxed, part of the glitches will be left untouched, while too strict values of these parameters can lead to the removal of pixels in the centre of the brightest sources. This effect is due to the fact that the timeline signal of a scan across those sources is very similar to glitches: the brightness rises high above the average values of the background, while its increase in the central area of these sources usually occurs quite sharply, as is the case for glitches. To circumvent this problem, a mask with the location of the sources can be passed to the task, in order to skip them when the glitches are determined. It is also advised not to use this kind of deglitching for observations which are expected to have a substantial area of extended emission, since there is usually not enough pure background to characterise the noise behaviour in these cases.

In Figure 3.11, an example is shown for a timeline before and after MMT deglitching is applied: the glitches, which clearly show up as outlying dots, have been removed after the deglitching. However, the MMT deglitching can also inadvertently remove real sky signals: Figure 3.12 depicts a concatenated timeline, on which all deglitched signals are indicated with coloured dots. It is obvious that a significant amount of these dots lie on the timeline, meaning it is likely most of them represent actual sky signals instead of glitches. At a later stage, we discarded MMT as the deglitcher, partly due to this false positive behaviour, but also because it is less well suited for Parallel Mode observations (a major part of our data reduction efforts), due to the reduced sampling frequency in the blue channel.

IIndLevelDeglitching

As mentioned earlier, and contrary to the MMT deglitching, which processes data in the temporal dimension, the second level deglitching operates on the spatial plane of projected PACS photometer data signals onto the sky, effectively using the redundancy in the sky coverage. This data should already be processed up to Level 1, and more specifically, it should have been flux calibrated with `photRespFlatfieldCorrection` for the second level deglitching to work properly, and in the case of cross-scan observations, the orthogonal scans should be concatenated. The first step of the second level deglitching is then to let the `MapIndexTask` generate a `MapIndex` of `MapElements`, each of which holds a reference to a specific detector or frames pixel at a certain time index contributing to the map pixel that `MapElement` belongs to. The `MapIndex` is

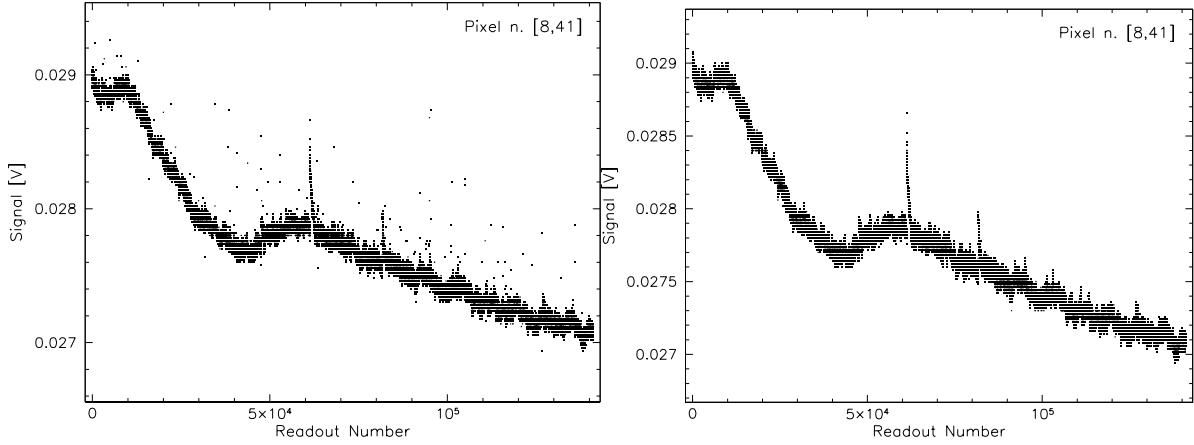


Figure 3.11: Removal of glitches with MMT deglitching. *Left:* Glitches stand out as individual dots, sometimes far outside of the timeline. *Right:* After deglitching, the overwhelming majority of the regular, positive glitches have been removed.

organised in the form of a three-dimensional data array, with the first 2 dimensions those of the eventual map image, while the third dimension gives access to the array of MapElements for that specific row and column (Figure 3.13). Each MapElement also contains the surface of the frames pixel and the fraction of its overlap with the corresponding map pixel.

The second part is then the second level deglitching itself, the `IIndLevelDeglitchTask`, which takes the previously generated MapIndex and for each map pixel separately performs a sigma clipping on the vector of flux values, for which the exact algorithm applied can even be completely user-defined. This is a very effective method for weeding out the glitches, as shown in Figure 3.14. A mask can be provided to the task, indicating which parts of the field should or should not be deglitched, allowing various parts of the observation to be treated with different deglitching parameters or even algorithms.

However, this approach still has a problem similar to the one encountered with MMT deglitching: if a strong gradient occurs, for instance when the central part of a source is very bright, even compared to its immediate surroundings within the source, the contributions from the frames pixels to certain map pixels may still be wrongly identified as a glitch. This is because the regular algorithm only looks at the complete flux values instead of taking into account the actual contributions due to the partial overlap between frames pixels and map pixels.

To circumvent this problem, a modified version of the algorithm adds together all contributions from frames pixels with the same time index, weighted according to their overlap with the map pixel, and then performs the same sigma clipping on the newly generated flux data vector of elements, none of which now have the same time index,

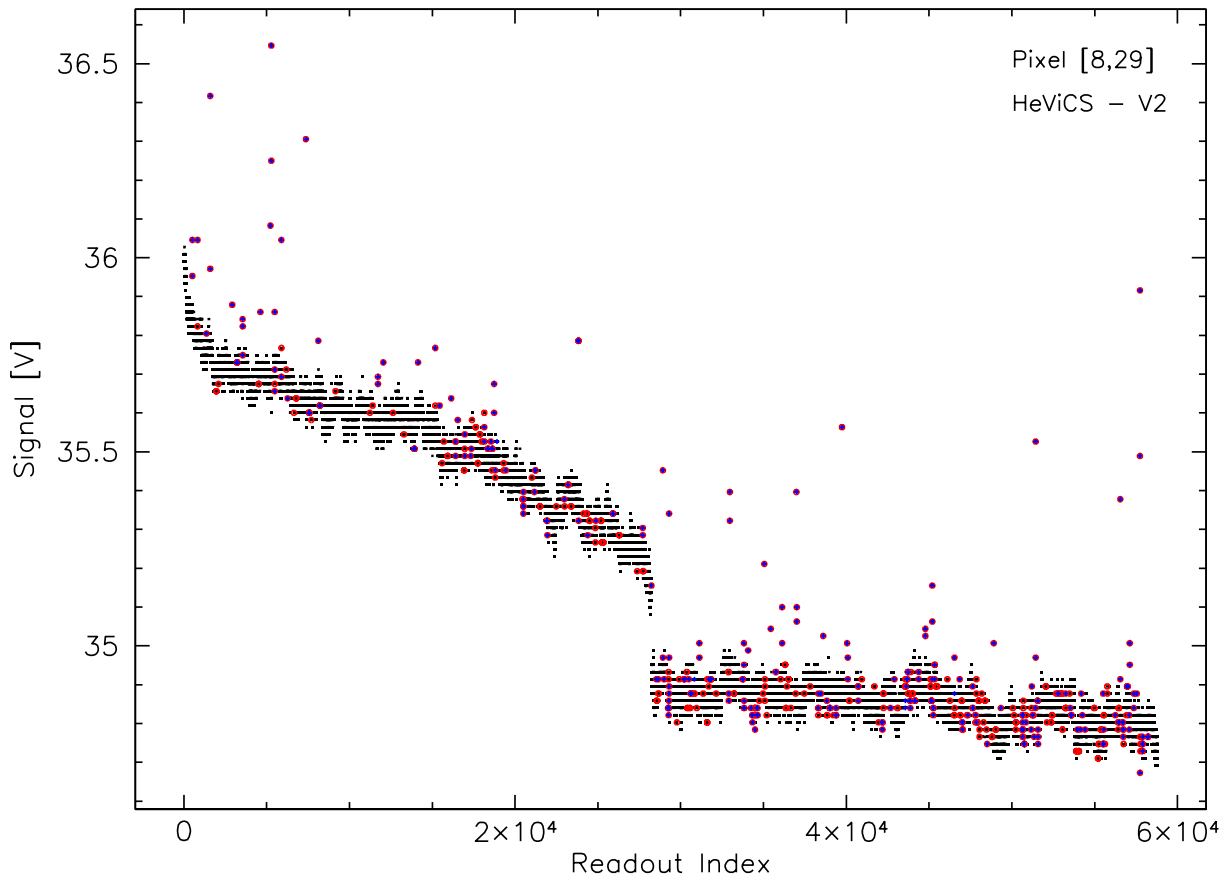


Figure 3.12: An example of a pixel readout timeline, showcasing the effect of MMT deglitching: nearly all isolated dots above and below the regular timeline are identified as glitches, while some dots on the timeline which most likely correspond to a genuine sky signal (bright source, faint source, or real background), are also masked as glitches. The red and blue dots were determined with the same deglitching parameters, but with a different calculation of the noise. In this particular case, the offset in the timeline about halfway is not caused by a signal jump, but it is due to joining two orthogonal observations of a cross-scan.

hence the name of time ordered deglitch vector. This approach works because a glitch usually appears in only one or two time frames, while a genuine sky signal will have a nearly constant flux value across all time frames. The only downside to this approach is that when a glitch does get detected, all contributions to that map pixel for that particular time index have to be removed, since the specific frames pixel responsible for it can no longer be determined.

Another issue with this algorithm is the memory requirement it poses: maintaining all the information contained in the MapElements leads to about 12 GiB (gibibyte, 2^{30} bytes) of necessary RAM memory for each hour of observation, rendering the deglitching of large observations nearly impossible on most high-end computers. To resolve this situation, the second level deglitching algorithm contains a few modifications to drastically reduce the total amount of data stored in memory at any particular

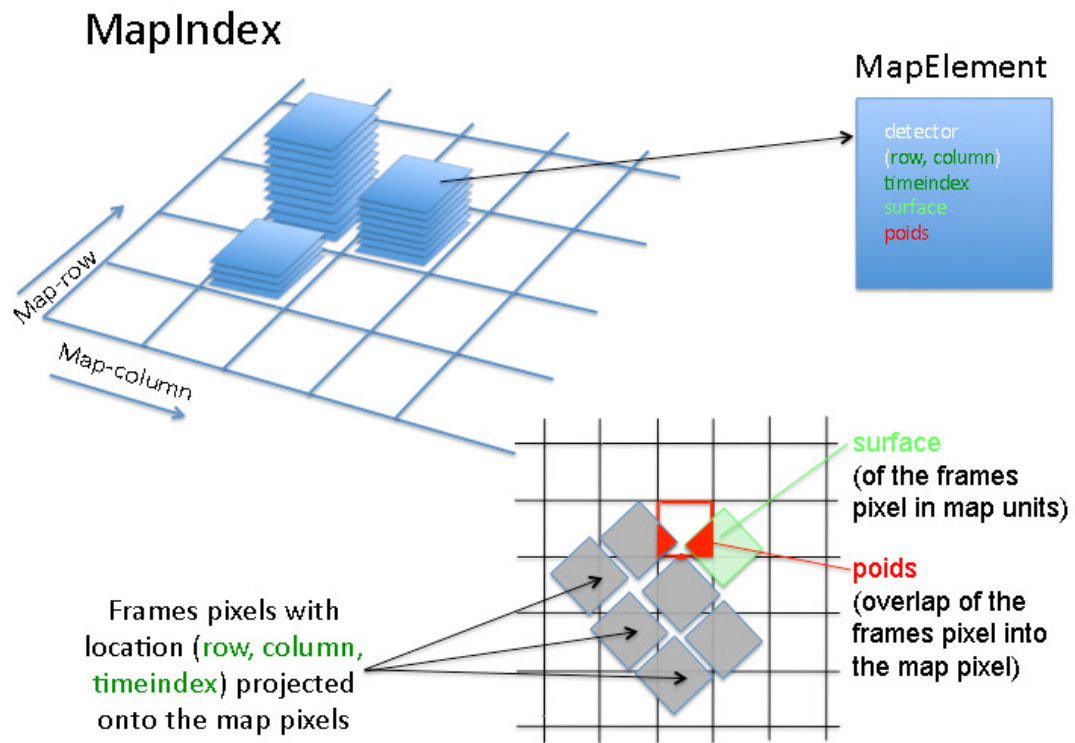


Figure 3.13: An overview of the MapIndex and MapElement structures used for the second level deglitching. For each pixel of the final map, the MapIndex contains all MapElements referencing the detector array or frames pixels contributing to that map pixel, along with the surface of these frames pixels and the fraction of that surface with which they contribute to that map pixel.

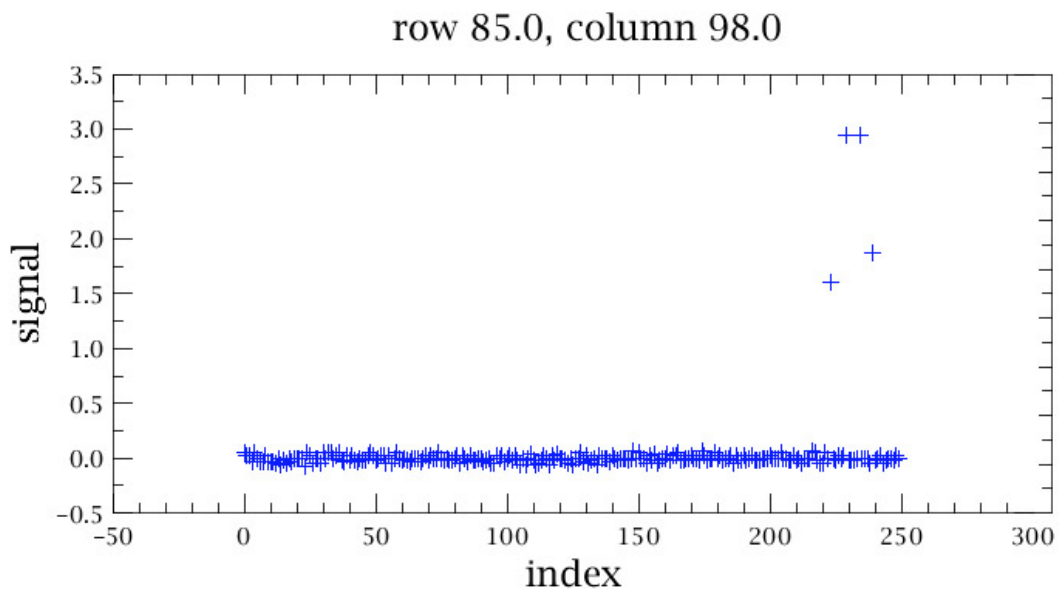


Figure 3.14: The vector of all signal values from various detector pixels for a specific map pixel. Glitches are easily recognised with flux values deviating substantially from the mean.

time. The main tweak is the use of a `SlimMapIndex`, which keeps only the detector pixel number and the time index, dropping all other information kept by the `MapElements` in the regular algorithm. This leads to only 2 GiB of memory footprint per hour of observation. Another approach to save memory is splitting up the entire observation into smaller rectangular tiles when building a `MapIndex`, thereby dividing the necessary total amount of memory by the number of tiles. When the `MapIndex` for a certain tile is complete, the deglitching is performed on that tile only, the imaging information for it is stored, and the memory is vacated to treat the next tile. A final major memory saving method is the `MapDeglitchTask`, which basically performs the functionality of both steps in the regular second level deglitching algorithm, but without maintaining any `MapIndex`: it handles each map pixel separately, each time searching for the relevant detector pixels and then performing the actual deglitching. Of course, in all these instances the trade-off for less memory is a reduction in processing speed to a varying degree for the different modifications, leading to a longer time before the entire observation is deglitched.

Long glitches

Treating the previously discussed signal jumps, sometimes called long glitches due to their relatively long-term effect on the signal timelines, generally requires a different approach from the two previous methods. In an early phase of the pipeline development, when no second level deglitching was available yet, we made an effort to automatically identify these jumps as a first step, in order to be able to remove them at a later stage. Recognising the beginning of such a jump is rather easy: when a chosen number of readouts for a particular detector pixel timeline have values at least $N\sigma$ either above or below the average level of a moving window with a selected number of preceding readouts, where N is also predefined, it can be reasonably assumed the start of a long glitch has been found. Since the signal timelines almost invariably show a clear trend instead of just varying around a constant average value, locating the end of the glitch is a lot trickier. To address this issue, the average slope for the entire timeline is used to determine when the signal values reach more or less expected values again, and thus define the final readout of the signal jump.

However, this procedure proved prohibitively slow, and in the end it was abandoned, since various mapping methods have intermediate steps which greatly reduce the problem: a high-pass filter, which is used often, flattens out these long glitches for the most part, since they usually last longer than the applied filter length, while stacking several repetitions of orthogonal scans together almost completely washes out these signal jumps, since they are highly unlikely to occur at the exact same sky coordi-

nates. The second level deglitching, which only became available at a later stage, can also handle these long glitches to a certain extent, in contrast to the MMT deglitching, which has no such capabilities.

3.4

Map-making: generating images from PACS data

In order to further reduce the resulting Level 1 PACS photometry data from the previous section up to Level 2 images, a mapping algorithm has to be applied. Several algorithms were examined, and the three major ones are discussed in this section, after which a comparison between them is made.

3.4.1 PhotProject

The L1 data, for which the reduction was described in the previous section, still contains the $1/f$ noise, and a simple way to remove it, is to apply a high-pass filter. This is a moving box of a specified width either side of the readout, scanning the individual timelines of the various detector pixels, determining the median flux value within the box, or the mean if the user so wishes, and in the end subtracting these new timelines of medians from the original ones, which comes down to subtracting the median of each individual box from its central readout pixel. The `highPassFilter` task can also be provided with a mask of positions which should not be filtered. The downside of this method is that, along with the $1/f$ noise, any structure with a size above the filter width will be removed as well in the final map, so this width has to be chosen carefully with the scientific case in mind. For example in HeViCS (see next Chapter for a full discussion), one of the goals is the detection of cirrus emission, and, if possible, also intracluster dust. Since these structures have a very large scale compared to the field, it is extremely difficult, if not impossible, to find an appropriate filter width.

Usually a final step before the actual mapping is to filter out the turn-arounds between scan legs, to guarantee a nearly constant scan speed for the entirety of the mapped observation. The mapping algorithm of the `photProject` task takes the observation scans, preferably concatenated, and produces the final map, along with the associated world coordinate system (WCS), exposure, noise and weight maps, using the coaddition of images as in the drizzle method described by Fruchter & Hook (2002). Since $1/f$ noise removal is not part of this algorithm, it is assumed the signal has already been treated with the `highPassFilter` task prior to its ingestion into the `photProject` task. The user can optionally provide a specified WCS to be used in the projection, as well as the size reduction of the detector pixels before the coaddition. The latter option is useful to

reduce the cross-correlated noise between pixels, associated with the image projection itself, as discussed quantitatively in Casertano et al. (2000, appendix).

The image generated, in some cases coadded with other observations of the same field, can then be used to produce the masks for the deglitching and the high-pass filtering, feeding them back into the pipeline using the `photReadMaskFromImage` task, finally resulting in a better map. These masks were produced using the automatic image detection algorithm `SExtractor` (Bertin & Arnouts 1996): the resulting segmentation map has zero values in background pixels, while all connected pixels associated with a particular detected source have the same non-zero value, corresponding with the source's rank number in the generated catalogue. This image can then be easily modified into a mask covering sources.

3.4.2 MADmap

The Microwave Anisotropy Dataset mapper (MADmap, Cantalupo et al. 2010) was originally designed for use with cosmic microwave background (CMB) experiment data and has been incorporated into HIPE. It is an optimal, maximum-likelihood map-making method which eliminates the uncorrelated $1/f$ noise from the Time Ordered Data (TOD), while at the same time retaining the large scale sky signals. Assuming a predetermined noise model of the detectors, the set of linear equations representing the projection inversion problem is solved with a conjugate gradient method due to the problem's large dimension, resulting in the best possible least-square fit to the data.

MADmap can only work properly if all instrument artifacts have been removed from the timeline. The required data reduction consists of two main parts, the first of which is basically the standard data reduction from L0 to L1. However, the second level deglitching is preferred over MMT deglitching, since the latter can confuse MADmap. The second main part of the data reduction is denominated as the preprocessing and consists of the removal of correlated noise and signal drifts other than the $1/f$ noise. This preprocessing, together with the time ordering of the data and the actual map-making, leads up to Level 2.5, combining at least two orthogonal scans into one concatenated data stream to produce an optimal map.

Due to the assumption within the MADmap algorithm that only the $1/f$ noise is still present in the data stream, it is critically important that all other forms of noise and drifts have been mitigated before the map-making is started. These drifts are divided into pixel-to-pixel offset variation, module-to-module drift (signifying differences between subarrays) and global correlated drift. They are sequentially corrected

for with the `photOffsetCorr`, `photModuleDriftCorrection` and `photGlobalDriftCorrection` tasks.

All but the $1/f$ noise should now have been removed from the timelines, and the TOD array can be built as a rearrangement of the detector pixel readouts with the `makeTodArray` task, based on the default or user-supplied WCS, taking proper precautions for masked and bad data. Finally the map is generated with the `runMadMap` task, which allows to pass some parameters for the conjugate gradient routine used and to choose between the regular MADmap solution or a `NaiveMap`, which is comparable to a `photProject` map but not as accurate. In both cases the resulting map contains sky, coverage and error images along with the appropriate WCS.

Usually this map still has some artifacts present within it, almost invariably around bright point sources, where crosses with large positive or negative sky values appear, oriented along the scan directions. As outlined in Piazzo et al. (2012), the post-processing `photCorrMadmapArtifacts` task can remove these through iteratively estimating the artifacts and producing improved maps with the estimated artifacts removed, until it converges.

However, the absence of a solution to this problem until very recently, together with the memory usage, which will be discussed further on in Section 4.4.3, has led to this mapping method being dropped from consideration for generating the maps of the *Herschel* observing programmes described in the following Chapters.

3.4.3 Scanamorphos

Scanamorphos (Roussel 2013) is a map-making program written in the Interactive Data Language (IDL), and developed to be used with *Herschel* PACS and SPIRE data, although with minor modifications, it is more widely usable for most scanning instruments with adequate redundancy. It is able to map observational data into an image, removing most noise components such as drifts and glitches, by using only the inherent redundancy available within the observation, without assuming any specific noise model. It can handle nearly all kinds of observational fields, containing both point sources and extended structure at any scale, but since the *Herschel* instruments are not absolute photometers and as such the resulting maps still contain a global offset, the user is left to decide how to estimate the background level, depending on the intended scientific applications.

The drifts present in any PACS observation have for the most part a relatively slow nature compared to the sampling rate of the data acquisition. This slow component of the drift is also called low-frequency noise, and can be split into two main components, a thermal and a non-thermal term. The thermal component is connected to the

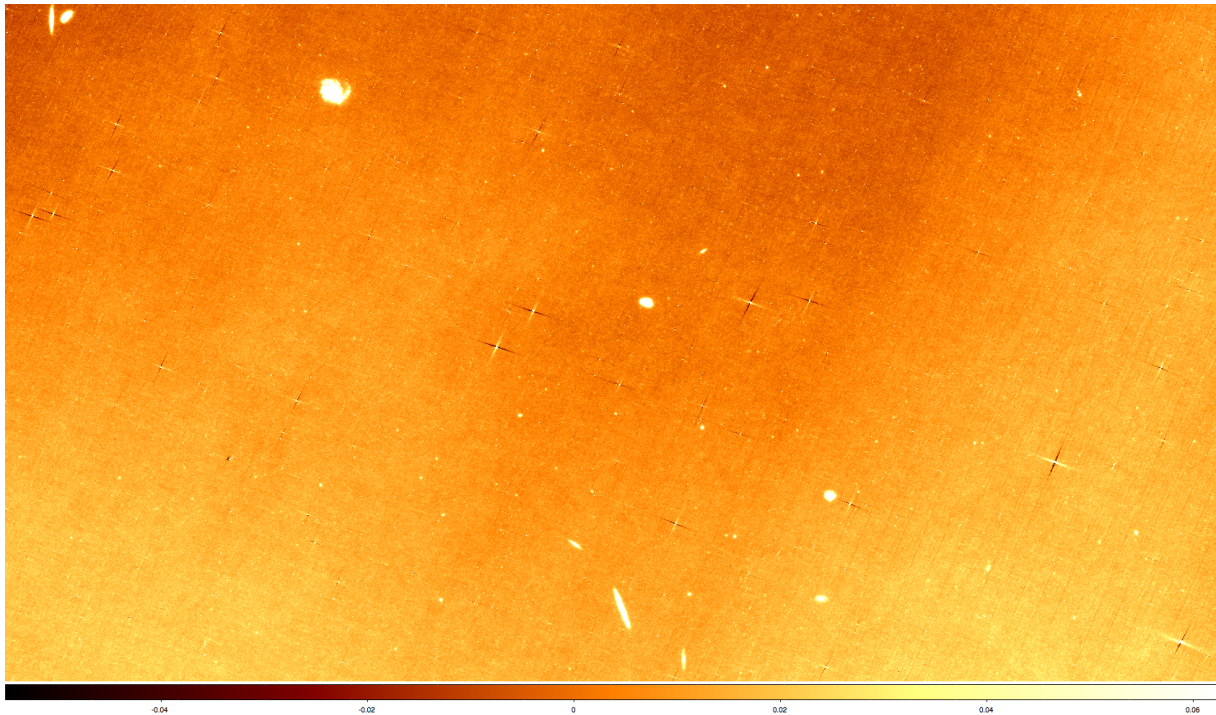


Figure 3.15: A MADmap image in the red band. The artifacts around point sources are clearly visible as crosses with highly positive and/or negative fluxes. The background gradient is not physical, but a result of the sub-optimal preprocessing.

temperature variations of the instrument and the noise it produces is therefore globally correlated between all bolometer pixels. The non-thermal term can be attributed to flicker noise and is as such uncorrelated between pixels, as it is caused by the read-out electronics and the solid-state physics of the detector. Both these components are considered as the only remaining contributions to the brightness drifts, since all other instrumental effects are removed during the data reduction up to Level 1.

At the start of the algorithm, Scanamorphos expects L1 data, but the deglitching can be skipped since Scanamorphos contains a form of second level deglitching. The data are first exported out of HIPE and then converted in IDL into a format the algorithm can handle. At least a scan and a cross-scan with a large enough opening angle between the scan directions should be provided to Scanamorphos, but it can also handle individual scans, though the results then still contain some low-frequency noise.

The algorithm splits the two components of the low-frequency noise in a slightly different way: the average drift common to all array pixels, and the individual drifts, uncorrelated for all pixels individually. The first step in the algorithm is to set up map and sky coordinates, and in the case of large data volumes, the dataset can be sliced into several spatial blocks if required to reduce the memory usage. If desired, the data from the turnarounds between scan legs can be included, albeit with inferior cover-

age.

For the removal of the drifts, the algorithms makes sensible use of the redundancy, meaning any sky pixel is normally covered by several array pixels scanning over it at different moments in time. By comparing the various detected signal values for a particular sky pixel, the statistics allow to infer the different drift components, first the average, common drift and then the individual, uncorrelated drifts, since some terms can cancel each other out, while others reduce to zero if averaged over sufficient samples. This means that therefore the actual sky brightness can also be determined after subtraction of the drifts from the timelines.

Finally, the sky, weight, error and low-frequency noise maps are projected and written to one or several separate FITS files, making use of the internal statistics to correctly weigh each signal. This projection assumes axisymmetric instead of square pixels and uses the fairly standard drizzle method (Fruchter & Hook 2002) with slightly reduced array pixel areas. These approximations barely affect the final maps. In case the dataset was sliced, the different slices are stitched back together at the end, making sure the brightness levels in overlapping regions are matched.

Since the algorithm can handle both faint and bright, complex fields, and treats point sources and extended emission cautiously, resulting in good quality maps without too much disturbing artifacts, this mapping method is becoming more and more the standard for making maps of PACS data. We can say that we have made a small contribution to its development, since we have been using it already from an early stage, providing feedback on problems we encountered when processing our observational data, and suggesting to include an option to detect transient sources (e.g. asteroids, see Section 4.6).

3.4.4 Comparison between different mapping methods

Given the fact that the high-pass filtering necessary for the photProject task washes out all structure larger than the filter box size, this mapping method is primarily meant for point source observations, and should only be used for small extended sources when the filter width is adjusted to be larger than the intended targets.

Memory requirements

The necessary amount of computer memory for the PACS data reduction is closely related to the amount of data taken during the observation. The rate at which this observational data is generated, is the product of the number of array pixels, the sampling frequency and the storage size of each measurement. Given that these values are stored

in an 8-byte double data type and that, apart from the signal, also the noise and the sky coordinates are recorded, the data volume for the blue channel easily reaches ~ 2.5 GiB per hour, while that for the red channel is ~ 0.6 GiB per hour. In parallel mode, the blue channel data rate is roughly halved due to the lower sampling frequency.

Nevertheless, memory requirements for any map-making method will obviously increase for longer PACS observations, potentially exceeding the memory of even high-performance computers for the deepest observations of large fields. Crucially, the MADmap algorithm within HIPE has no provision if the internal memory is not sufficient for the demands of a certain observation, other than to export the data outside HIPE and use a native version of the MADmap programme, which is capable of distributed computing. Scanamorphos by default offers the option to slice the observation into smaller fields which are finally mosaicked back together as mentioned earlier, while the PhotProject algorithm has the same capability through the `IIndLevelDeglitchTask`. This latter task can directly generate the final map using the same internal HIPE routines as PhotProject, and in the case of a slicing of the observation, the map is built up incrementally with the different smaller parts.

MADmap was actually not used for any of the *Herschel* observations discussed further on in the following Chapters, due to this unreliable memory requirement: for instance, the 8 scans of a single HeViCS field (see next Chapter; each combination of 2 scans takes about 16 hours of observation time) in the green band could not be processed together, even on a computer with 256 GiB or RAM. The fact that it was not used by the majority of the other large *Herschel* programmes, that the maps it produced were of generally inferior quality compared to the other mapping methods, in particular due to the artifacts of the aforementioned negative crosses, and that it has only very recently improved to an acceptable level, has further contributed to the abandonment of this map-making algorithm for the further analysis discussed here and for the observations in the next Chapters.

Data reduction processing time

Even though we have quite powerful computers at our disposal, a complete data reduction still takes a very long time, lasting up to several days for particularly large observations. Taking the 8 scans single HeViCS field as an example, the PhotProject including second level deglitching can last between 16 and 20 hours, for both the red and the blue channel. A considerable fraction of this time goes into the deglitching. Using Scanamorphos, the same data takes about 8 hours (both red and blue) to pre-process in HIPE, and then about 48–50 hours for the red and 70–80 hours for the blue channel.

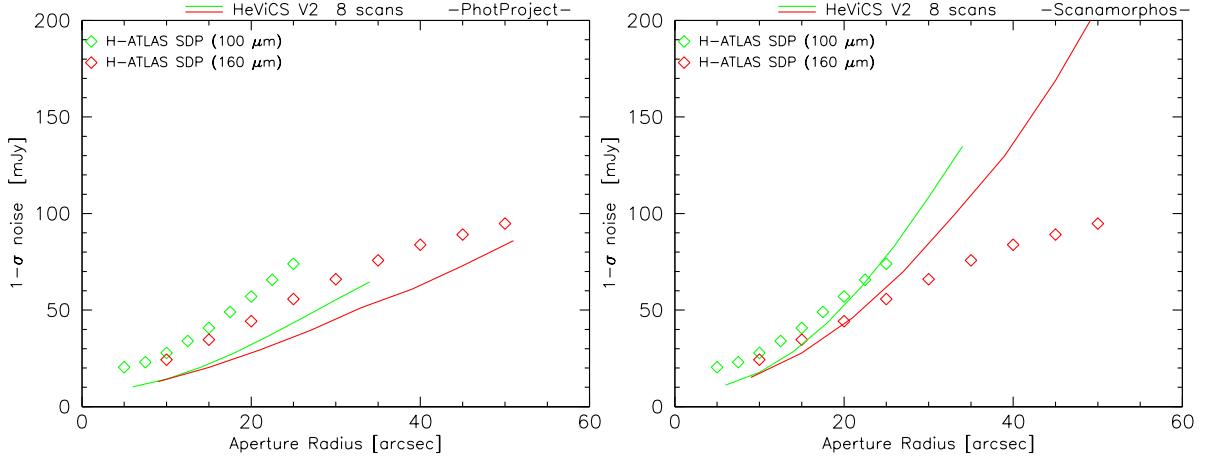


Figure 3.16: Flux noise measurements for different aperture sizes, for the green $100\ \mu\text{m}$ (green) and red $160\ \mu\text{m}$ (red) bands. For an explanation of HeViCS (lines), see next Chapter; H-ATLAS (diamonds, both panels using PhotProject) used the same observing strategy and field size as HeViCS, but covers only a single cross-scan. *Left:* PhotProject mapping method. *Right:* Scanamorphos mapping method.

Noise measurements

Following the same method described in Ibar et al. (2010), the noise characteristics for these mapping methods were compared by randomly selecting thousands of points from map regions with homogeneous coverage. This means they have undergone the same number of scans, thus areas near the edge are excluded, and overlapping areas between different fields are approached as single fields, or compared with other overlapping regions with the same number of scans. The maps used for this analysis were made in Parallel Mode at a scan speed of $60''$, an observing strategy often used, especially in the *Herschel* programmes discussed in the next Chapter. For a detailed description of the HeViCS project, see Chapter 4; H-ATLAS (Eales et al. 2010) is an Open Time Key Project covering several areas in the sky with the same field sizes as the ones in HeViCS, but only performing a single cross-scan.

For each of the random points, the total fluxes were measured within apertures of increasing size, with aperture corrections applied. From these measurements, all points with values deviating by more than 2.5σ from the median were iteratively excluded to avoid contamination by actual sources, and this was repeated until no more points had to be rejected. The resulting 1σ noise values are shown in Figure 3.16. It shows that using PhotProject, the noise for a certain aperture radius is more or less inversely proportional to the square root of the number of scans and thus of the integration time. For a Scanamorphos generated map of the H-ATLAS SDP data (noise measurements not shown here), the same also holds.

The larger noise levels obtained for Scanamorphos compared to those for PhotProject

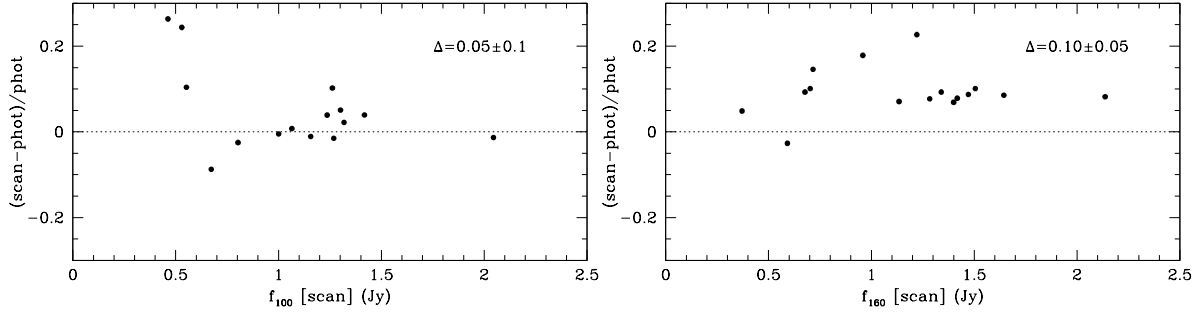


Figure 3.17: Flux comparison between PhotProject and Scanamorphos, with average difference indicated in each panel. *Left:* Green 100 μm band. *Right:* Red 160 μm band.

are most likely inherent to this type of mapping technique using the redundancy in the observational data. However, part of it could also be due to the fact that the high-pass filtering within PhotProject more or less ‘flattens’ all signals, including the background and thus leading to a lower overall noise.

Flux comparison

To compare the fluxes resulting from both map-making algorithms, a small sample of galaxies in the HeViCS fields were selected to perform aperture photometry on them. The relative differences are plotted in Figure 3.17. The averaged differences indicate that in Scanamorphos maps, we measure about 5% more flux at 100 μm than PhotProject does and about 10% more at 160 μm , but differences for individual galaxies can reach 20% or even above. The origin for this discrepancy probably lies in the negative contribution towards the total flux caused by the negative bowls (see Section 3.4.5) in PhotProject maps, which are very hard to completely remove.

3.4.5 Remaining artifacts

Negative bowls

As mentioned earlier, the high-pass filtering can be done with a mask, and this is in fact a necessity for bright point sources and regions of extended emission, because without it, the moving median box can overshoot in the value it has to subtract from the signal data stream, having an adverse effect on the resulting map (Figure 3.18).

This happens as follows: as the box is moving along the scan direction over a point-like source or some extended emission such as a nearby galaxy, the median over the whole of the box remains relatively flat at first, but as more and more of the bright emission lies within the box, the median increases, until at some point the median

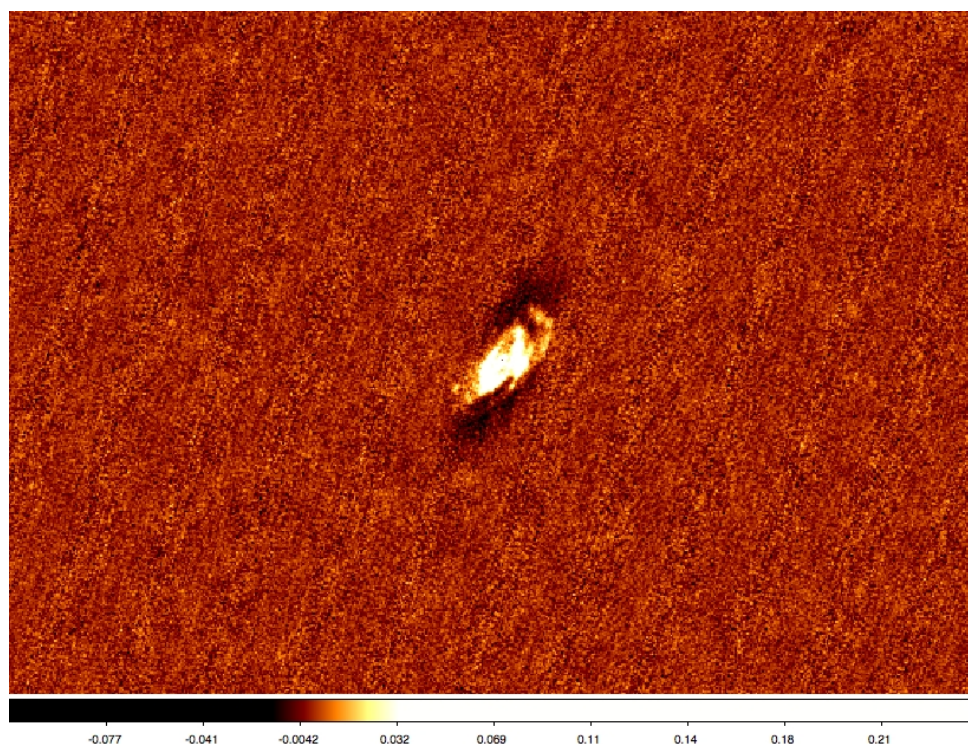


Figure 3.18: Overshooting or negative bowl surrounding an extended source along the scan direction.

level must cross with the actual signal values. Approximately from the moment the median started to rise, up to this point, the median levels are actually higher than the sky signal, and as these medians are subtracted from the signal, a band with negative brightness along the scan direction is the result for point sources, or in the case of extended emission, an entire, nearly surrounding, area of negative sky values is created, a so-called negative bowl. Masking the sources from the high-pass filtering diminishes this situation, but it has been found that for extended sources, the masking area for the source should be slightly enlarged by a few pixels beyond the extent of the source itself to remove the majority of this effect, and yet part of the problem still persists in some cases.

The masking is also useful for another reason: since the median box moving over a bright source can at some point result in a median quite a lot higher than the surrounding background, part of the flux can be wrongly removed from the source by the high-pass filtering. This problem can again be largely avoided by properly masking sources. However, a downside is that by using a mask, the $1/f$ noise is partly left behind in the masked area, since it is no longer properly removed there. The overall conclusion is that using PhotProject is not advisable when dealing with extended sources, while it still is very useful for point sources.

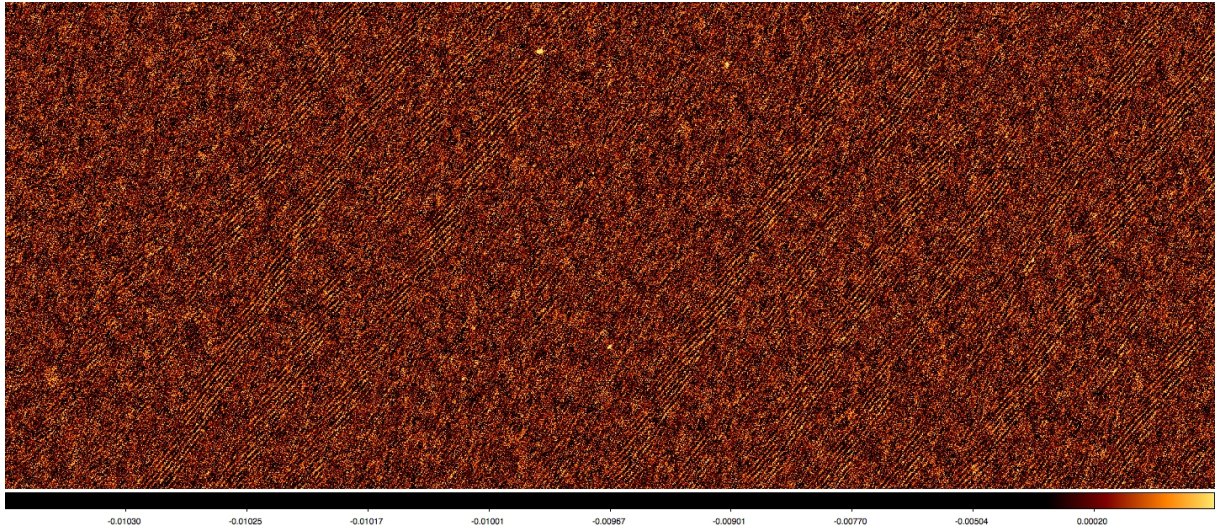


Figure 3.19: An example of interference badly affecting a PACS 100 map. Various scan legs with the typical bands pattern caused by this problem are visible.

Interference

It has been noticed in some observations that the final map shows a strange pattern somewhat comparable to that of the famous double-slit experiment, with alternating brightened and darkened sky signals. Over the whole of all observations, this kind of event occurs intermittently in the blue photometer data and although they are mostly short-lived, they can adversely affect an observation (Figure 3.19). The cause for this behaviour has not been found yet, but the assumption is that it may be connected to the switching on and off of some of the solar panels. Lacking a clear explanation for it, removing this kind of artifact is as good as impossible at this point. However, depending on the total number of scans available, combining all scans can greatly reduce its impact on the overall map.

The *Herschel* Virgo Cluster Survey

4

The knowledge about the PACS pipeline and map-making algorithms discussed in the previous Chapter, was gathered within the framework of a number of *Herschel* observing programmes to generate the maps necessary for their scientific analysis. This PACS data reduction formed part of the work for this thesis, along with devising the best observation strategy and field coverages for some of the proposals. These projects were devised to observe nearby galaxies and clusters, and will be discussed, along with some of their results, in this and the following Chapters: the *Herschel* Virgo Cluster Survey and a follow-up *Herschel* Fornax Cluster Survey in this Chapter, the *Herschel* Exploitation of Local Galaxy Andromeda in Chapter 5, and the *HERschel* Observations of Edge-on Spirals in Chapter 6.

In this Chapter, the *Herschel* Virgo Cluster Survey is introduced in Section 4.1 and its goals and observations described in Section 4.2. The specific PACS data reduction and flux measurements for two different sample approaches are discussed in Sections 4.3 and 4.4, respectively. Section 4.5 covers a selection of scientific results, while Section 4.7 gives an overview of a follow-up proposal covering the Fornax Cluster. Finally, some rather unexpected, serendipitous observations of asteroids, which are unrelated to the original proposal's objectives are discussed in Section 4.6.

Concerning this chapter, I do not claim a major scientific contribution to most papers within the HeViCS collaboration. My contribution to these papers was concentrated on producing properly reduced PACS maps and providing extensive comments on how to use them correctly in different situations. As demonstrated in the previous Chapter, producing high-quality PACS maps is a time-consuming and non-trivial task, particularly for the large-area and deep observations that are almost unique for the HeViCS programme. It needs to be stressed that the PACS data constituted an invaluable resource. For instance, in FIR SED fitting, the shorter wavelength PACS data points are indispensable to constrain the peak of the SED and thus the corresponding dust temperature, since using only the SPIRE data points would lead to a degeneracy. The results discussed in Section 4.5 are an excellent example of this.

4.1 The *Herschel* Virgo Cluster Survey (HeViCS): an introduction

The Virgo cluster has a cluster virial mass of $\sim 2.5 \times 10^{14} M_{\odot}$ (Girardi et al. 1998; Rines & Diaferio 2006) and contains ~ 2000 optically catalogued galaxies (Virgo Cluster Catalogue (VCC), Binggeli et al. 1985). Due to it being the closest cluster of galaxies to our own Galaxy at a distance of ~ 17 Mpc (Gavazzi et al. 1999, and references therein) and thus allowing the highest level of detail available, it has been and continues to be the most extensively studied cluster, more so than any other, over almost the entire electromagnetic spectrum, from X-ray to radio wavelengths. Therefore, it was a logical step to close the only remaining gap at FIR wavelengths, making use of the high sensitivity and survey capabilities the *Herschel Space Observatory* provides, and the proposed *Herschel* Virgo Cluster Survey (HeViCS, Davies et al. 2010) was approved as an Open Time Key Project.

4.2 Scientific goals & survey description

Clusters not only show the morphological segregation effect (Dressler 1980), with the early-type galaxy population increasing as the local galaxy density rises, the galaxies within them also have a clear difference from isolated field galaxies: many of them have significantly less atomic gas (Haynes & Giovanelli 1984) and a less extended HI distribution. It is this deficiency in neutral gas which is the likely origin for the lower star-formation rates (Lewis et al. 2002; Gómez et al. 2003), the truncation of star-forming discs (Boselli & Gavazzi 2006; Koopmann et al. 2006) and the higher metal content of cluster galaxies (Skillman et al. 1996). Blind surveys at several wavelengths have also revealed the presence between the cluster galaxies of intra-cluster star forming regions, extended low surface brightness tidal streams stretching over tens of kpc (Mihos et al. 2005) and ram pressure stripped gas streams originating from infalling galaxies (Oosterloo & van Gorkom 2005).

Contrary to the well-studied stars, metals, neutral and molecular gas in clusters, very little is known about the properties of cold dust (below 30 K) in cluster galaxies and in the Intra-Cluster Medium (ICM). Much can be learned about galaxy evolution as well as the accretion and enrichment history of galaxy clusters through a better understanding of the influence by the cluster environment on the dust cycle within a galaxy. In groups and clusters of galaxies, significant amounts of metals can be found between the galaxies (Renzini 1997), likely expelled out of them through supernovæ, tidal interaction or ram pressure stripping. Dust grains could also be driven into the ICM by these processes, but there still is a lack of evidence for dust grains in the intra-cluster

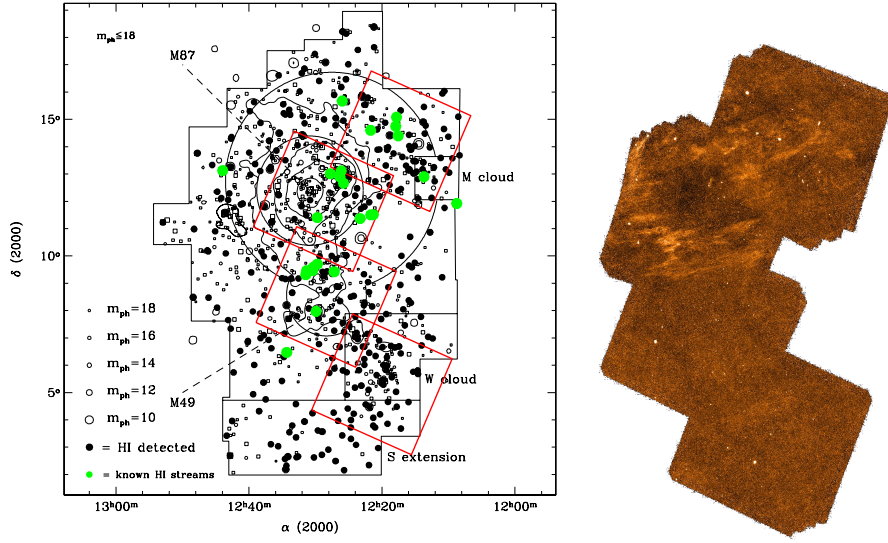


Figure 4.1: *Left:* The four observed fields of roughly 4×4 square degrees each, overlaid with red boxes on top of a schematic overview of the Virgo cluster. These fields are denoted V1 to V4 from the top to the bottom. *Right:* A complete SPIRE 250 μm map produced with all the fields, using the standard orientation (North is up, East is left).

gas, and indirect measurements of intra-cluster dust (Impey & He 1986; Maoz 1995; Stickel et al. 1998; Montier & Giard 2005) are still controversial.

Several *Herschel* Guaranteed Time Key Projects were designed to study the dust properties in nearby galaxies and its role in the star-formation cycle, but none of them could address the previously mentioned galaxy cluster issues, either because they were targeting limited areas around optically selected galaxies, or because the survey areas were specifically avoiding nearby clusters. To rectify this oversight, the *Herschel* Virgo Cluster Survey was proposed and later approved to carry out a wide area blind survey, covering ~ 60 square degrees of the Virgo cluster (Figure 4.1) and using both PACS and SPIRE in Parallel Mode. With the intended sensitivity target of reaching the confusion limit of $\sim 1 \text{ MJy sr}^{-1}$ at 250 μm , a few hundred of the known Virgo galaxies in the covered fields were expected to be detected across all observed wavelengths, meaning the survey can act as a local cluster benchmark, comparing the results with those from environmental studies as well as field surveys and clusters at higher redshift.

In the proposal, a number of major scientific objectives for the survey were set out, as outlined below:

- **Intra-Cluster Medium:** The presence of any significant amount of dust in the diffuse structures of the intra-cluster medium remains an outstanding question (Zwicky 1957), but its metal enrichment clearly indicates substantial interactions between galaxies and their environment, while intra-cluster stars (Feldmeier et al.

1998) can give rise to in situ dust production. Observationally based estimates of the total dust mass within the central 1 Mpc diameter sphere for the Virgo cluster are of the order $10^{10} M_{\odot}$, resulting in $\sim 1 \text{ MJy sr}^{-1}$ surface brightness at $250 \mu\text{m}$ if the dust has a temperature of 20 K, although models predict brightness values one or two orders of magnitude lower (Popescu et al. 2000b). To reach the better sensitivity requirements this poses, the maps should be smoothed over several pixels, with the Virgo galaxies and the Galactic cirrus subtracted, the latter based on existing HI observations with sufficient spatial resolution.

- Cold dust in the extreme outskirts of galaxies: Most other Key Projects, such as e.g. HRS (*Herschel* Reference Survey, Boselli et al. 2010b) and KINGFISH (Key Insights on Nearby Galaxies: A Far-Infrared Survey with *Herschel*, Kennicutt et al. 2011), only encompass pointed observations of galaxies, while extended dust emission far beyond the optical size is only observable with the HeViCS blind wide survey approach. Earlier nearby galaxy observations have already shown that cold dust can indeed be more extended than the stellar component (Alton et al. 1998b; Davies et al. 1999), while dust features (Howk & Savage 1997) and PAH emission (Irwin et al. 2007) have been identified at distances high above the disc plane of edge-on galaxies.
- The FIR/sub-mm luminosity functions: The first luminosity function (LF) for a local cluster in the wavelength range $80\text{--}600 \mu\text{m}$, based on a FIR instead of optically selected sample, can give vital clues on galaxy formation and evolution and its faint-end slope allows the quantification of the local FIR background, which is important for high redshift sub-mm observations. Through integration of LFs, the total infrared (TIR) luminosity, which is considered to be a good star formation rate (SFR) indicator, can be determined and hence the total star formation density for the entire cluster can be quantified. The combination of the TIR with the total UV luminosity permits a quantification of the UV attenuation.
- Modelling the UV to sub-mm SED and the dust mass function: For the quantification of total dust mass and dust temperature in galaxies, the SED shape within the $1\text{--}1000 \mu\text{m}$ range is crucial. Previous studies only had a few infrared flux measurements to extrapolate the TIR emission from models. Combining both PACS and SPIRE data points permits to include various dust components in the models, leading to much more accurate total dust emission and dust mass estimates. The resulting UV to sub-mm SEDs can be used to quantify the interstellar radiation field and the dust obscuration in different objects. The calculation of the total dust content for each galaxy leads the creation of a total dust mass function.
- Dust in dE and low surface brightness galaxies: Although dwarf and low surface

brightness galaxies (LSBG) were considered to have little dust and low SFRs and metallicities, recent studies have either directly shown the presence of dust, or indirectly suggested its presence, in at least a fraction of these LSB and dE galaxies. The *Herschel* data allows unprecedented determination of dust properties and distribution in LSBG, while stacking of the data at dE locations may lead to a statistical detection of their FIR emission, potentially unveiling some questions about their origins.

- Dust in cluster irregular galaxies: In late-type galaxies, the mass content in the cold dust component is several orders of magnitude higher than in the warm component. The scarce studies of cold dust properties in the irregular galaxies indicated that later-type systems have a higher dust surface density and a colder dust component than in regular spirals. Some blue compact dwarfs (BCDs) even have a dominant cold dust emission over the warm dust emission. The HeViCS survey increases the available FIR observation statistics for these types of galaxies substantially.
- Dust in cluster elliptical galaxies: Although recent FIR observations point to dust masses of 10^5 to more than $10^7 M_{\odot}$ in elliptical galaxies (e.g. Vlahakis et al. 2005), once thought to be devoid of gas and dust, a statistically significant survey beyond $100 \mu\text{m}$ had been lacking. This situation has been dispelled with HeViCS, allowing SEDs of elliptical galaxies to be modelled including FIR emission, thereby giving valuable information about the properties, the amount and the life cycle of the different dust components within this type of galaxy. This ultimately permits a quantification of the amount of star formation as well.

As it is a blind, wide area survey, the fast scan speed of $60''/\text{s}$ and the PACS/SPIRE parallel mode were chosen to cover the FIR/sub-mm SED for the largest possible area within a certain timeframe, using the $100 \mu\text{m}$ filter for the PACS blue channel. To achieve the required sensitivity of $\sim 1 \text{ MJy sr}^{-1}$ at $250 \mu\text{m}$, the confusion limit for the SPIRE instrument at that wavelength, each scan needs to be repeated 8 times. The total area is divided into 4 different fields (Figure 4.1), measuring $245' \times 230'$ (about 15.6 square degrees) in size for the region guaranteed to be covered by both instruments, given the $\sim 21'$ focal plane offset between PACS and SPIRE, and the 8 scans for each field are grouped into concatenations of a nominal and an orthogonal scan each, to reduce the striping caused by the $1/f$ noise. The size was determined to fit each concatenation of 2 scans within the 18 hours of observational time per OD: one scan takes 9 hours, a concatenation of 2 scans lasts 17.9 hours, resulting in a total requested time of 285.7 hours.

Those figures were determined based on the pre-flight estimates of the observation

planning tool, HSpot. The actual observations took less time than expected due to a more efficient scanning strategy, and the remaining part of the awarded time was used to carry out dedicated PACS 70 μm filter observations of specific galaxies in the fields with no or poor 70 μm *Spitzer* data, as well as a spectroscopic study of a sample of dwarf galaxies within the survey area.

4.3

PACS data

The various scans for the different fields were not observed in one go, but rather over several consecutive observing windows. Consequently, the applied data reduction techniques evolved and improved as more and more data became available. The following description corresponds to the PACS data reduction used for the first release of the complete dataset of all scans for all four fields (Auld et al. 2013).

The PACS 100 and 160 μm maps were obtained by exploiting the naive projection task `photProject` in HIPE (v7.3.0), following a similar approach as described by Ibar et al. (2010) and in the previous Chapter. Map making was performed in two steps: for each single scan, maps were obtained using the standard data reduction pipeline, but with the entire VCC galaxies masked out. In these maps, the $1/f$ noise was corrected for by applying a high-pass filter with a length of 20 and 40 frames for the 100 and 160 μm map, respectively. Taking into account the scan speed and the different sampling frequency in parallel mode, this corresponds to a spatial filter length of slightly more than $8'$ for both channels — the filter box size is actually twice the given frames parameter, taking into account this number of frames before as well as after the current readout. Deglitching was performed by means of the sigma-clipping standard algorithm (the `IIndLevelDeglitchTask` task in HIPE, with $\sigma = 3$). These preliminary maps were used to identify and mask bright, extended non-VCC sources, and to fine-tune the deglitching. The masks were then applied to the calibrated timelines using a flux threshold set to 2.5σ , and the minimum number of pixels above the threshold, for a source to be detected, was set to 48 and 24 for the 100 and 160 μm channels, respectively. In order to minimise the high-pass filtering over-subtraction, the masks were enlarged, by adding 4 and 2 pixels to the edges of the detected sources, for the 100 and 160 μm maps, respectively.

In a second step, the data were reduced again. This time, the deglitching task was applied before high-pass filtering, with the bright sources being masked to avoid unwanted flux removal from their brightest parts. Then, the masked, deglitched timelines were high-pass filtered, with a filter length of 10 and 20 frames for 100 and 160 μm respectively, now corresponding to a spatial filter length of about $4'$ for both channels. At

this point the timelines for the eight scans were joined together. After this, the second-level deglitching task was run to remove glitches from the bright sources and, finally, individual tile maps were produced with the photProject task.

Due to the enormous volume of data in a PACS observation, the HIPE map maker was only capable of combining 8 cross-scans from an individual tile into a single mosaic. The individual tiles were then combined into mosaics using the SWARP¹ package.

The PACS beams at 100 and 160 μm are elongated along the scan direction due to the onboard averaging of the PACS data applied to fit the total amount of data within the daily communication window using the limited data transfer rate. Averaging together the 8-scan data, taken at different observing angles, results in approximately circular beams. These are roughly Gaussian in shape with FWHM values for the 100 & 160 μm beams of 9.4'' and 13.4'' respectively and the corresponding map pixel sizes were set to 2'' and 3'' respectively. The PACS instrumental error maps from the HIPE pipeline were not yet fully reliable, as the noise is not properly propagated throughout the PACS pipeline, so PACS errors were estimated directly from the signal maps, using apertures on blank regions of sky. The standard deviations of the background in the PACS maps are 1.9 and 1.2 mJy pixel⁻¹ for the 160 and 100 μm channels respectively in the areas covered by 8 scans. This decreases to 1.3 and 0.8 mJy pixel⁻¹ in the overlapping regions. This is consistent with a $\sqrt{t_{\text{int}}}$ decrease, where t_{int} is the integration time, indicating that the noise of the background in the PACS maps is still dominated by instrumental noise.

4.4

PACS fluxes

After completion of at least one cross-scan observation for each of the 4 fields, a FIR selected sample of galaxies was taken from the single cross-scan data, resulting in the Bright Galaxy Sample (BGS, Davies et al. 2012). In Auld et al. (2013), a catalogue of FIR properties is constructed for all optically selected VCC Virgo cluster galaxies within the HeViCS fields, using the complete *Herschel* dataset with all scans for this proposal. The following discussion describes the sample selection and the steps taken for the aperture photometry to measure their PACS fluxes and estimate the total uncertainties, but similar methods were applied to the SPIRE data as well, to ensure the catalogue is as homogeneous as possible. In fact, a strict requirement for the VCC selected sample was that a galaxy needed to be detected at SPIRE 250 μm , the data with the best combination of sensitivity and resolution, to restrict the possibility of illegitimate background

¹ <http://www.astromatic.net/software/swarp>

sources making it into the catalogue.

4.4.1 Sample selection

The first objective of the Bright Galaxy Sample was to produce a bright far-infrared selected sample, choosing the 500 μm SPIRE data to carry out the source selection (Davies et al. 2012). The justification for this choice is the combination of the lowest resolution in the *Herschel* data with the fact that the majority of galaxies emit the least flux in this band out of the *Herschel* bands, virtually guaranteeing detection in all of them, as well as the unexplored state of this part of the spectrum.

The automatic image detection algorithm SExtractor (Bertin & Arnouts 1996) was applied to obtain an objective selection, requiring more than 30 connected pixels with flux levels of at least $1.5\sigma_{500}$ to minimise faint sources contaminating the background. The resulting 500 μm flux density limit is ~ 0.1 Jy, for objects with a diameter larger than $1.4''$. Correspondence with known Virgo Cluster galaxies was checked for each source, resulting in a final sample of 78 bright, high signal-to-noise (S/N) Virgo Cluster objects, the faintest galaxy reaching a S/N of ~ 15 . This sample constitutes a 12% fraction of the 629 VCC confirmed cluster member galaxies within the HeViCS fields listed by GOLDMINE (Gavazzi et al. 2003). Rejected sources were either background sources behind the Virgo Cluster, or part of extended galactic cirrus emission.

For the BGS aperture photometry, the 500 μm data was used to visually determine elliptical apertures, with a concentric annulus defining the sky. These were then also applied to the maps for the other wavelengths, after smoothing and regridding them to the same resolution and pixel scale as the 500 μm maps.

A total of 750 sources out of 1076 VCC objects (Binggeli et al. 1985) with photographic magnitude $m_{\text{pg}} \leq 18$ fall within the region covered by the full HeViCS dataset covering an area of $\sim 84 \text{ deg}^2$, which is larger than the $\sim 55 \text{ deg}^2$ area of the full-depth coverage region. The difference is due to the larger area actually observed for a single field to compensate for the focal plane offset between the two instruments and still cover the entire guaranteed area with both. For each identified target, the optical disc was overplotted on the 250 μm image, using optical parameters such as position, ellipticity, position angle (taken from HyperLEDA (Paturel et al. 2003)) and optical diameter d_{25} , estimated from the photographic plates in the original VCC quoted in GOLDMINE (Gavazzi et al. 2003).

It is known from earlier results (e.g. Pohlen et al. 2010; Cortese et al. 2010) that optical and FIR emission are fairly well correlated in late-type galaxies lacking truncation of their gas discs. Hence the optical ellipse parameters form a good basis for FIR flux measurement in late-types, while early-types usually exhibit point-like FIR emission. A

few instance of the latter show extended, irregular emission (e.g. M 86) or synchrotron dominated radiation from the AGN jets (e.g. M 87, Baes et al. 2010a, discussed in Section 4.5.1).

4.4.2 Automated aperture photometry flux measurements

For the VCC based sample, an automated procedure was set up to perform the aperture photometry and measure the FIR fluxes at the *Herschel* wavelengths. An example of the different steps is shown in Figure 4.2 for the SPIRE 250 μm reference wavelength.

As a start, for each galaxy a 200×200 pixel sub-image centred on it was selected from the overall map (Figure 4.2(a)), masking all Virgo galaxies in the sub-image with ellipses corresponding to their $1.5 \times d_{25}$ optical extent, or, in the case of bright point-like sources, with circular apertures. These masks were convolved with the relevant Gaussian beam profile in each band, thus allowing for edge-ons and galaxies with d_{25} sizes smaller than the beam for any *Herschel* band. The sub-image region was increased in size to up to 1200 pixels for PACS maps when the optical size was too extended.

The background was estimated using the IDL fitting routine SFIT. This background nominally consists of foreground cirrus as well as bright or unresolved background sources. Since the instrumental noise is dominant in PACS maps, a second order polynomial fit was sufficient, with a 95% flux clip using only the remaining pixels to curtail the influence of bright background sources. Figure 4.2(b) gives an example of a background estimate, which is then subtracted to get a new sub-image (Figure 4.2(c)).

The next step was to create annuli with increasing radius around the galaxy's optical centre, based on the optical ellipse parameters. The total flux, surface brightness, aperture noise (described further on) and the S/N (the ratio of total flux within the annulus to the aperture noise for that area) were measured for each annulus. Based on the S/N radial profile, the estimated edge of the galaxy was then defined as the cut-off where the S/N fell below 2 (black dashed line in Figures 4.2(d), (e), (f) & (g)). This led to a new mask, replacing the old one, and the procedure was iterated. After convergence, fluxes and aperture noises had aperture corrections applied as in Ibar et al. (2010).

Special care was taken when total aperture S/N was below 3: the sub-image was convolved with the PSF for each band and the flux within the PSF's FWHM at the optical centre was measured. A Gaussian was fitted to the negative fluxes in the histogram of flux values to estimate the noise of the convolved map as the width of the Gaussian. As a result, only point sources above 3σ were considered as detected, and the width was considered to be the aperture noise in the total uncertainty calculation.

After completion, visual inspection of optical images from GOLDMINE and the Digital

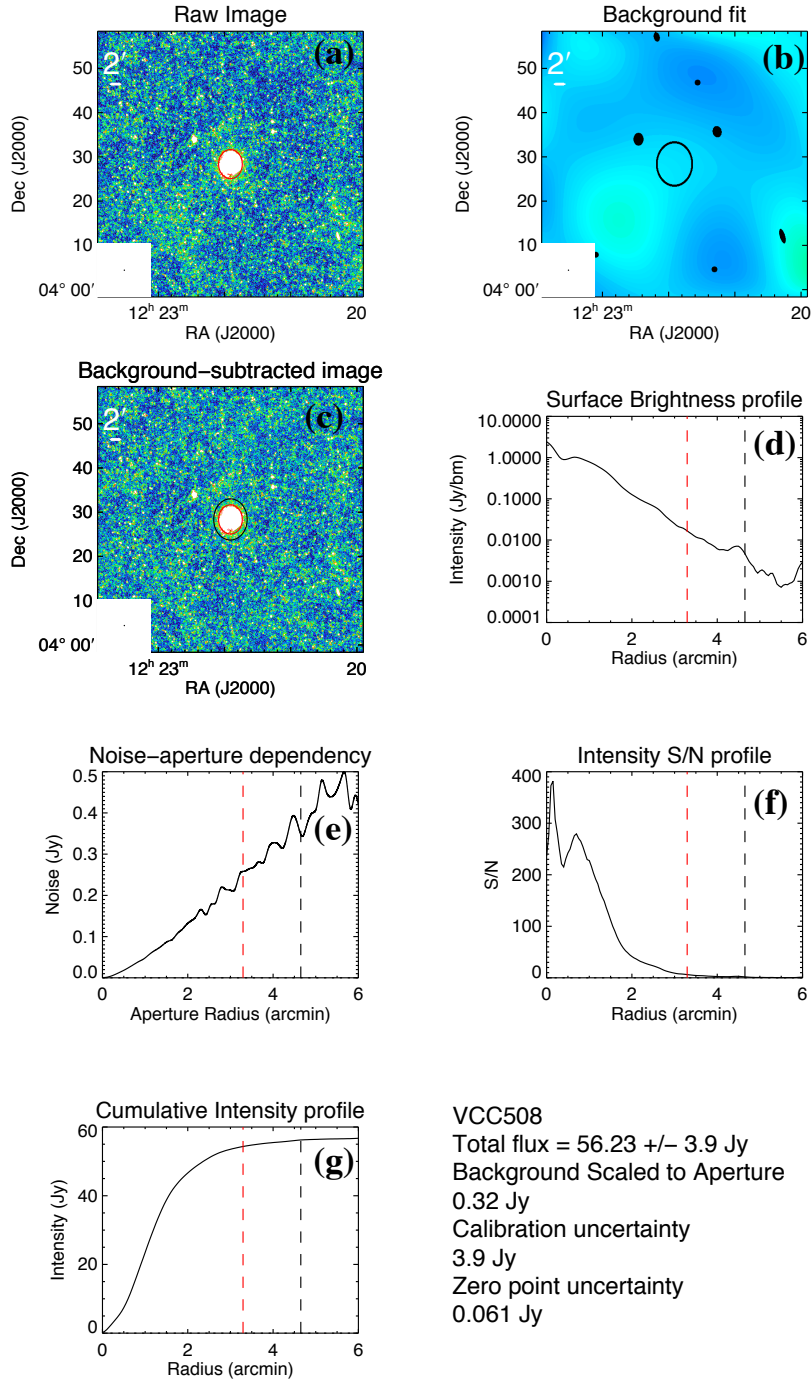


Figure 4.2: Example products from the fitting process for M 61 (VCC 508) at $250 \mu\text{m}$. **(a)** The raw sub-image extracted from the full HeViCS mosaic. The d_{25} limit is outlined in red, the $250 \mu\text{m}$ beam is given to scale at the bottom left of the image. **(b)** The estimate of the background from the masked image. The ellipse is explained in the text. **(c)** The resultant background-subtracted sub-image on which radial plots and flux measurements are performed. **(d)** Radial plot of surface brightness. **(e)** Radial dependence of the total noise in a circular aperture. **(f)** and **(g)** Radial plots of S/N and cumulative intensity respectively. Optical (d_{25}) and FIR limits are indicated by the red and black dashed lines respectively (Auld et al. 2013).

Sky Survey assessed the validity of the cut-off radii. In cases of contamination by nearby bright cirrus or background galaxies, this radius was manually redefined, or the galaxy was excluded from the catalogue of detections, affecting $\sim 10\%$ of the total number of detections. Colour corrections were omitted, as these are left to potential users having the required knowledge of the source's colour.

4.4.3 Total uncertainty estimates

A total of three different types of uncertainties added up to the final uncertainty measurements: the calibration uncertainty, σ_{cal} , the aperture uncertainty, σ_{aper} and the zero-point uncertainty, σ_{zero} . These contributions were added in quadrature:

$$\sigma_{\text{total}}^2 = \sigma_{\text{cal}}^2 + \sigma_{\text{aper}}^2 + \sigma_{\text{zero}}^2 \quad (4.1)$$

Various sources with different models went into the PACS calibration, so its uncertainty is rather complicated. Point sources have a quoted 2.2% correlated uncertainty, and 3% and 4% uncorrelated uncertainties at 100 μm and 160 μm , respectively, but with different observation, data reduction and analysis methods than the ones used for the HeViCS PACS data. An agreement to within 5-20% between PACS 160 μm and MIPS 160 μm data was noted in a Technical Report², albeit using two different map-making schemes to the ones used for HeViCS. For the Bright Galaxy Sample, this uncertainty was assumed to be 15% (Ibar et al. 2010). Increased knowledge about the calibration has justified the use of a value of 12%, including the correlated uncertainty, for the VCC based sample.

To estimate the aperture uncertainty in the VCC sample, a method similar to the one used for the noise measurements described in Section was used, but this time with square apertures and a 3σ cut, repeating until convergence. The aperture noise was set to the final value of the standard deviation, without trying to separate the confusion and the instrumental noise. This analysis was performed on both the sub-images used for the automated photometry, and the least cirrus-contaminated, southern-most field. The latter was rebinned using pixels of the appropriate aperture size, subtracting the mean of surrounding pixels as the background, and repeated sigma-clipping was applied. The results are plotted in Figure 4.3, with aperture size indicated as the radius of circular apertures with equal area to the used square apertures.

This same Figure 4.3 shows that aperture corrections become important for smaller sources of similar size as the beam. The expected white noise $\propto n_{\text{px}}^{0.5}$ increase seems

² Technical Report: "Assessment analysis of the extended emission calibration for the PACS red channel", Version 1.0, April 2012
<https://nhscdmz2.ipac.caltech.edu/pacs/docs/Photometer/PICC-NHSC-TR-034.pdf>

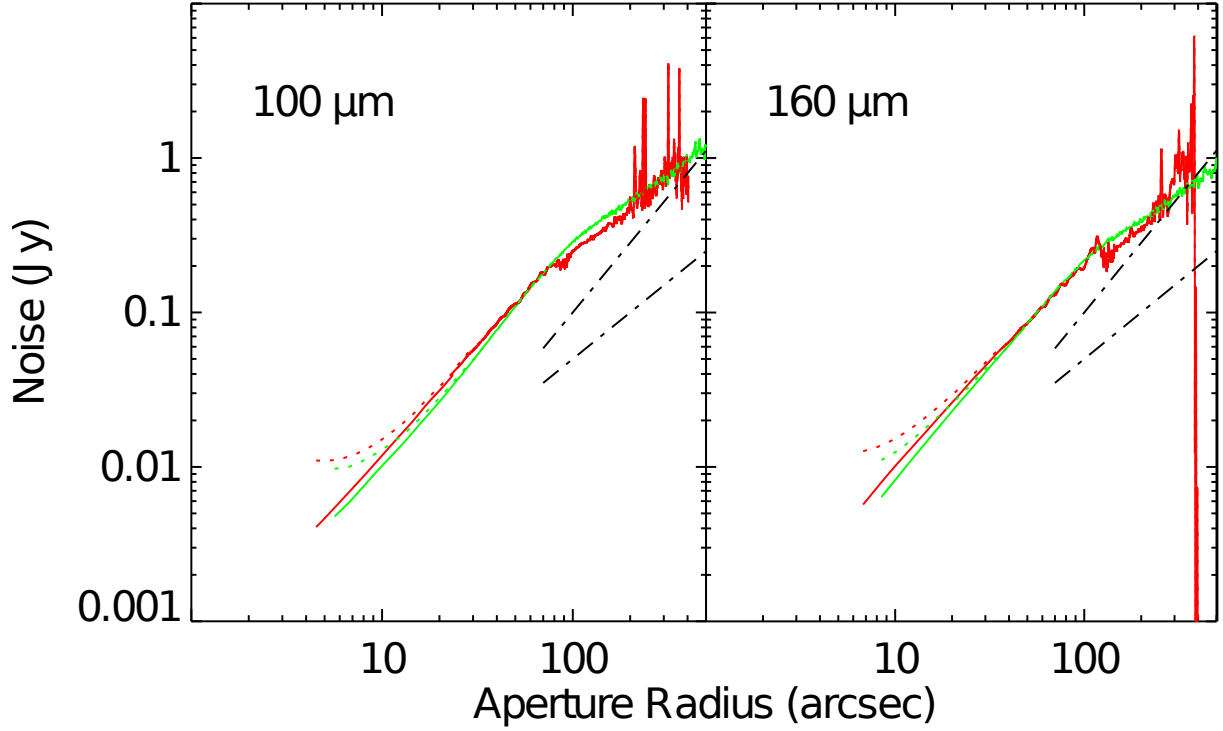


Figure 4.3: Aperture noise variation with circular aperture radius for PACS 100 (*left*) and 160 μm (*right*) data. Green lines are apertures measured from the entire, full-depth region within the southern tile. Red lines show the combined results from sub-images that were extracted from the entire map to perform photometry on individual targets. Dotted lines show the same data with aperture corrections applied. Overplotted dot-dashed lines show $\sigma_{\text{aper}} \propto n_{\text{px}}^{0.5}$ and $\sigma_{\text{aper}} \propto n_{\text{px}}^{0.75}$ relationships for comparison (Auld et al. 2013).

to only hold for the sub-images from large radii onwards, while all other cases agree better with a $n_{\text{px}}^{0.75}$ dependence. The cause for this different behaviour is likely connected to the distinct background estimations. Despite the noisy data, the relatively good correspondence with Gaussian noise for large radii puts enough confidence in the sub-image background subtraction on these scales. Since the PACS data is relatively unaffected by cirrus and background sources, the unexpected $n_{\text{px}}^{0.75}$ dependence is likely caused by an unaccounted error source, possibly connected to the map-making itself.

The map of the background fit was used to estimate the zero-point errors: within the source aperture, its standard deviation was measured and then multiplied by the number of pixels within the aperture. Only the rare, extended low-surface brightness sources had a significant contribution from this type of uncertainty to the total.

Table 4.1: Linear fit parameters to comparisons of *Herschel* fluxes from the HeViCS Bright Galaxy Sample with literature values. Uncertainties are shown in parentheses (Davies et al. 2012).

Wavelength (μm)	Gradient	Intercept
100 ^a	1.16 (± 0.02)	-0.69 (± 0.47)
100 ^b	2.52 (± 0.16)	-3.51 (± 1.71)
160 ^c	0.97 (± 0.02)	1.16 (± 0.56)
160/170 ^d	0.60 (± 0.05)	2.40 (± 1.12)
160/170 ^{de}	0.94 (± 0.05)	0.16 (± 0.48)
160/170 ^b	0.93 (± 0.05)	2.11 (± 1.47)

^a IRAS (GOLDMINE Gavazzi et al. 2003)

^b ISO (Tuffs et al. 2002)

^c *Spitzer*/MIPS (Bendo et al. 2012b,c)

^d ISO (Stickel et al. 2004)

^e Excluding NGC 4192

4.4.4 Verification of flux measurements

For the Bright Galaxy Sample, the PACS data were compared with literature values. From the GOLDMINE database, *IRAS* 100 μm fluxes were retrieved for 73 out of the BGS 78 galaxies. Twelve galaxies cross-matched with the *ISO* 100 and 170 μm data taken from Tuffs et al. (2002), while the ISOPHOT 170 μm Serendipity Survey (Stickel et al. 2004) has 14 galaxies in common with the BGS. For 44 out of the 78 galaxies, *Spitzer* 160 μm data was available.

The relations between the PACS 100 μm fluxes for the BGS galaxies on the one hand and the *IRAS* and *ISO* 100 μm data on the other hand are shown in the left panel of Figure 4.4, while the right panel contains the comparison of the PACS 160 μm fluxes with the *Spitzer*/MIPS 160 μm and the *ISO* 170 μm data. The identifications of clear outliers are indicated. The parameters resulting from the linear least square fits between the PACS and literature data are given in Table 4.1. The close proximity of NGC 4567 and 4568 to each other makes it difficult to separate them in the *ISO* data due to the lower resolution, explaining the outlying NGC 4567 PACS flux. The large discrepancy between the PACS 160 μm fluxes and the *ISO* 170 μm data from Stickel et al. (2004) can be attributed almost entirely to NGC 4192, since its removal from the comparison leads to a correlation much closer to 1:1 (Table 4.1).

For the VCC selected sample, the PACS fluxes were verified by comparing them to literature measurements of Virgo galaxies from the *IRAS* Point Source Catalogue (PSC) and the *IRAS* Faint Source Catalogue (FSC) (Moshir et al. 1993), from the *ISO* 100 & 170 μm data (Tuffs et al. 2002), as well as the earlier BGS flux measurements (Davies

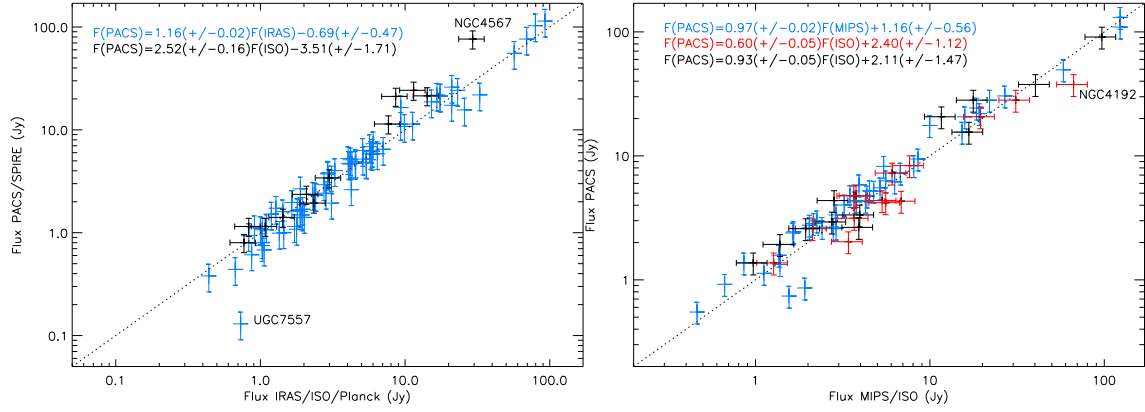


Figure 4.4: *Herschel* flux comparisons of Bright Galaxy Sample measurements with literature data. *Left:* The PACS 100 μm fluxes compared with *IRAS* (blue) and *ISO* (black) fluxes. *Right:* The PACS 160 μm fluxes compared with the *Spitzer* (MIPS) 160 μm (blue), the Stickel et al. (2004) *ISO* 170 μm (red) and the Tuffs et al. (2002), *ISO* 170 μm (black) fluxes. Linear least squares fit parameters are given in the top left corner of each panel. The black dashed line is the one to one relationship (Davies et al. 2012).

et al. 2012). Following the instrument team recommendations³, the PACS fluxes were colour corrected to compare them with the *ISO* data, while this is not required when comparing PACS 100 μm with *IRAS* 100 μm data. The correction factors were based on an assumed black-body temperature of 20 K, typical for dust in these galaxies (Davies et al. 2012).

Cross-matching of sources resulted in 70 galaxies from the *IRAS* PSC, 83 from the *IRAS* FSC, and 46 from Tuffs et al. (2002). The comparison with the BGS data was done with the original, manual apertures used for the BGS photometry, but this time applied to the full datasets to account for changes in flux calibration between the older, single cross-scan data and the newer, full dataset.

Table 4.2 gives the parameters, with 1σ uncertainties, for straight-line fits to the log-log plots shown in Figure 4.5. Within the scatter in the residuals, most of them are consistent with a 1:1 correlation, giving high confidence in the correctness of the fluxes in the catalogue without previous measurements. The PACS 100 μm fluxes tend to be higher than the *IRAS* 100 μm data, but this has already been independently identified by the instrument team and is under investigation. The discrepancy with the BGS measurements for VCC 785 at 160 μm is likely caused by the negative bowl: the 500 μm extent of the galaxy, used for the BGS aperture, covers a considerable part of it. The significant negative flux values associated to it therefore reduce the total flux substantially for the BGS measurement.

³ Technical Report: “PACS Photometer Passbands and Colour Correction Factors for Various Source SEDs”, Version 1.0, April 12, 2011
http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/cc_report_v1.pdf

Table 4.2: Linear fit parameters to comparisons of VCC selected *Herschel* fluxes with literature values. Uncertainties are shown in parentheses (Auld et al. 2013).

Wavelength (μm)	Gradient	Intercept	Scatter
100 ^a	1.11 (± 0.02)	-0.08 (± 0.02)	0.05
100 ^b	1.11 (± 0.02)	-0.09 (± 0.02)	0.08
100 ^c	1.02 (± 0.04)	0.16 (± 0.03)	0.13
100 ^d	0.97 (± 0.02)	-0.03 (± 0.02)	0.08
160 ^d	1.041 (± 0.006)	-0.048 (± 0.006)	0.02
160/170 ^c	1.08 (± 0.04)	-0.01 (± 0.03)	0.13

^a IRAS PSC

^b IRAS FSC

^c ISO (Tuffs et al. 2002)

^d BGS (Davies et al. 2012)

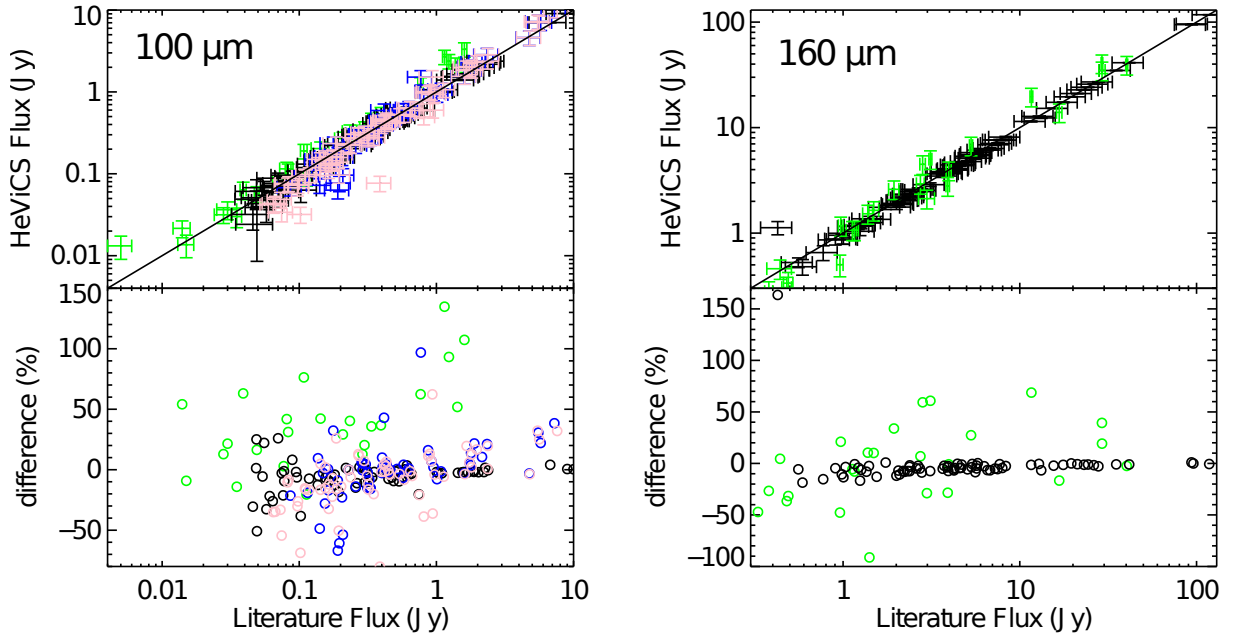


Figure 4.5: *Herschel* flux comparisons of the VCC based automated HeViCS measurements with ISO (green open circles), IRAS Point Source Catalogue (blue open circles), IRAS Faint Source Catalogue (pink open circles) and the HeViCS BGS (open black circles), for PACS 100 (*left*) and 160 μm (*right*) data. The 1:1 fit lines are shown in black, see the text and Table 4.2 for details of individual fits to the plots. The differences (in percentage) between HeViCS and the literature values are given in the bottom half of each plot. See text for further details on the outlier at 160 μm , VCC 785 (Auld et al. 2013).

The reduced PACS data were used extensively in a number of scientific papers written by the HeViCS consortium, even at an early stage, when only a few observations had been carried out. A few additional papers will be discussed here, especially those specifically using PACS data, the first three of which were based exclusively on the SDP data, meaning only a single cross-scan of the V2 field, covering the cluster's central region, was used.

Although they do not form an integral part of this thesis' work, they greatly benefitted from the investigation into the best map-making techniques as well as the production of the PACS maps, which was carried out on a relatively short time scale as a result. These maps were in fact essential to the science, since the two PACS data points are necessary to constrain the SED fitting. For instance, without both data points it would be nearly impossible to pinpoint with enough accuracy where the peak in the cold dust emission is located in the SED, leading to high uncertainties in the dust temperatures and masses.

4.5.1 FIR view of M 87

In Baes et al. (2010a), the nature of the FIR emission originating in M87, one of the most nearby radio galaxies at a distance of 16.7 Mpc (Mei et al. 2007), was investigated. Due to this close proximity, its features, especially the nucleus and the associated jet and lobes, have been extensively studied across most of the electromagnetic spectrum from radio over optical to X-ray wavelengths (e.g. Biretta et al. 1991; Meisenheimer et al. 1996; Böhringer et al. 2001; Perlman et al. 2001; Sparks et al. 2004; Perlman & Wilson 2005; Kovalev et al. 2007; Simionescu et al. 2008; Werner et al. 2010) with better resolution than elsewhere possible in comparable objects. Deep optical imaging of M87 has revealed faint dust features (Sparks et al. 1993; Ferrarese et al. 2006), raising the question of the origin of the FIR emission in this galaxy, especially from its nucleus. On the one hand, some studies claim to find evidence for an excess contribution over a power-law, caused by dust either in the ISM or around the nucleus (Perlman et al. 2007; Shi et al. 2007), while on the other hand, some papers argue that the MIR and FIR emission is generally consistent with synchrotron emission (Xilouris et al. 2004; Tan et al. 2008; Buson et al. 2009).

These studies were carried out with rather limited information about the FIR emission, compared to the data available at other wavelengths. The HeViCS SDP data extends the previously available FIR data with much improved resolution and sensitivity and

Table 4.3: Integrated *Herschel* fluxes for M87. The PACS and SPIRE flux density uncertainties were conservatively assumed to be 25%. The applied colour corrections were very small: 1.8% for PACS 100 and <1% for the other bands (Baes et al. 2010a).

Instrument	λ (μm)	F_λ (Jy)
PACS	100	0.517 ± 0.129
PACS	160	0.673 ± 0.168
SPIRE	250	0.860 ± 0.215
SPIRE	350	1.070 ± 0.267
SPIRE	500	1.430 ± 0.375

this new data, in combination with MIR, FIR, sub-mm and radio data from the literature, was used to examine the origin of the FIR emission.

As a first-order approach, the integrated *Herschel* fluxes were determined (Table 4.3) and combined with the other available data to study the global infrared-to-radio SED between 15 μm and 100 cm (Figure 4.6). The archival data came from instruments such as ISOCAM (Xilouris et al. 2004, 15 μm only), *Spitzer*/MIPS (Shi et al. 2007, 24, 70 & 160 μm), *IRAS* (Golombek et al. 1988, 25, 60 & 100 μm), SCUBA (Haas et al. 2004, 450 & 850 μm), WMAP (Wright et al. 2009), GBT MUSTANG and VLA (Cotton et al. 2009).

The best-fitting power law to all data points except those from *Herschel* has a slope $\alpha = -0.76$, while the fit through the SCUBA, GBT, WMAP and VLA data only, results in a slope $\alpha = -0.74$ (top panel in Figure 4.6). The residuals from the former power law are shown in Figure 4.6's bottom panel, indicating the *Herschel* data points are fully consistent with synchrotron radiation. Using Kormendy et al. (2009) photometry data for the ISRF in M87, the mean dust equilibrium temperature was determined to be $T = 23$ K with the SKIRT radiative transfer code (Baes et al. 2003, 2005a, 2011). The cyan line in Figure 4.6 is a modified black-body with this temperature and a total dust mass of $M_d = 7 \times 10^4 M_\odot$, fitted to the residuals' upper limits, clearly showing that the M87 global SED is incompatible with dust masses higher than $10^5 M_\odot$.

This simplified global analysis was confirmed by a spatially resolved second-order polynomial synchrotron model fitting the radio maps and a 24 μm *Spitzer*/MIPS image pixel-by-pixel (Figure 4.8), since its prediction for the emission at 250 μm is consistent with the observations (Figure 4.9, compared to the raw images in Figure 4.7). As M87 is also a luminous X-ray source, it is not surprising a substantial dust component seems to be absent. In conclusion, over the FIR wavelength range M87 can be considered a passive object with a synchrotron emitting central radio source, without a substantial diffuse dust component.

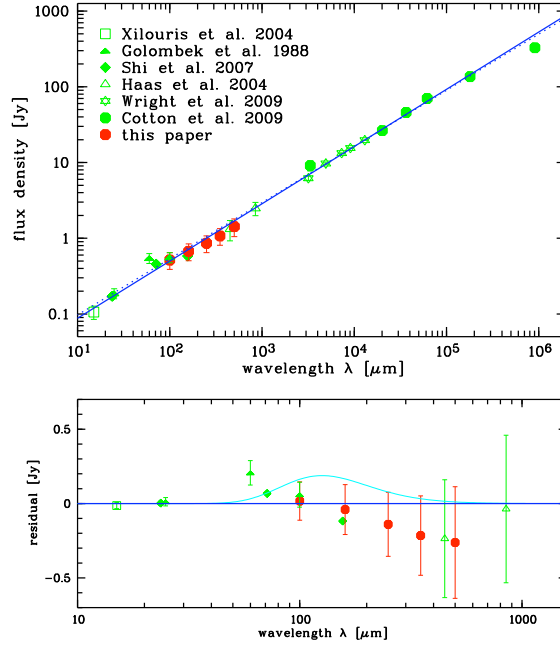


Figure 4.6: *Top:* the global SED of M87 from MIR to radio wavelengths. Error bars are invisible when smaller than the symbol size. The solid line in the plot is the best-fit power law of all used non-*Herschel* data; the dotted line has been fitted only to the SCUBA, GBT, WMAP, and VLA data. *Bottom:* residual between data and the best-fit synchrotron model in the IR–sub-mm wavelength range. The cyan line is a modified black-body model with $T = 23$ K and $M_d = 7 \times 10^4 M_\odot$; see text for more details (Baes et al. 2010a).

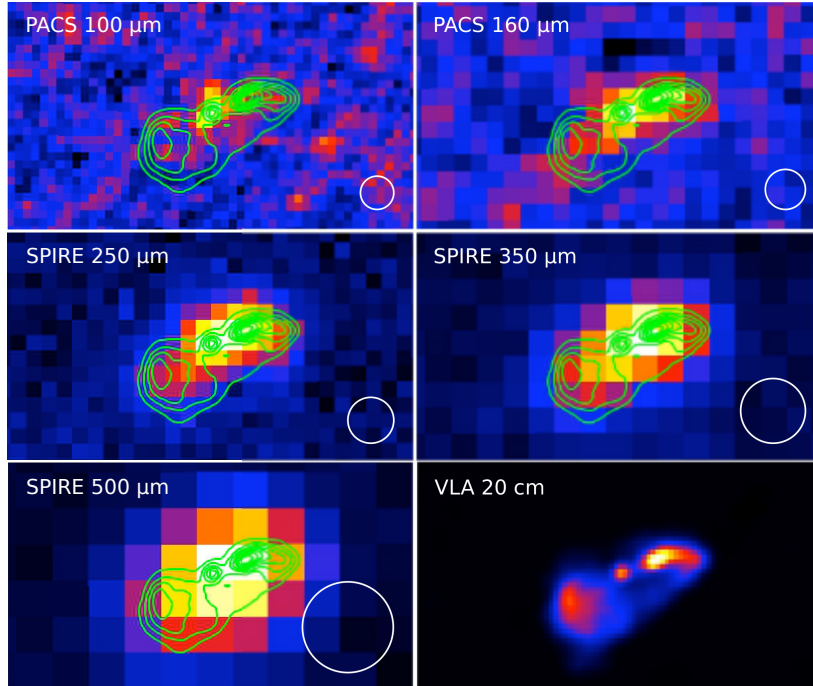


Figure 4.7: The *Herschel* view of M87's central regions. The 20 cm radio contours from the bottom right VLA 20 cm image taken from the FIRST survey have been overlaid on the *Herschel* images. The field of view of all images is $160'' \times 90''$, with beam sizes indicated in the bottom right corner of each panel (Baes et al. 2010a).

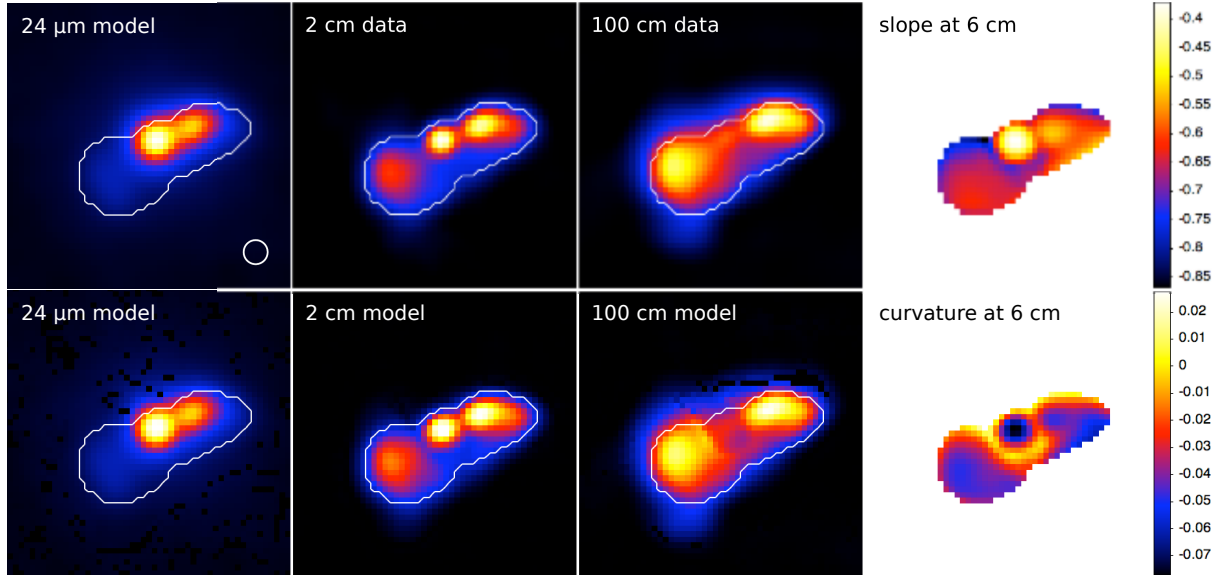


Figure 4.8: A data and synchrotron model comparison for M87. *Top row:* The observed *Spitzer* image of M87 at $24\ \mu\text{m}$ and VLA images at 2 cm and 100 cm, all convolved to the same resolution ($8.5''$ FWHM, $2''$ pixels). In each pixel, a synchrotron emission was fit to the *Spitzer*, GBT, and VLA data across the wavelength range between $24\ \mu\text{m}$ and 100 cm. The solid lines in the images show the region where the data are reliable at all wavelengths: outside this region, not all images could be used. *Bottom row:* The synchrotron model images corresponding to the images on the top row. The two rightmost images show the slope of the synchrotron fit and the curvature of the fit, both at 6 cm (Baes et al. 2010a).

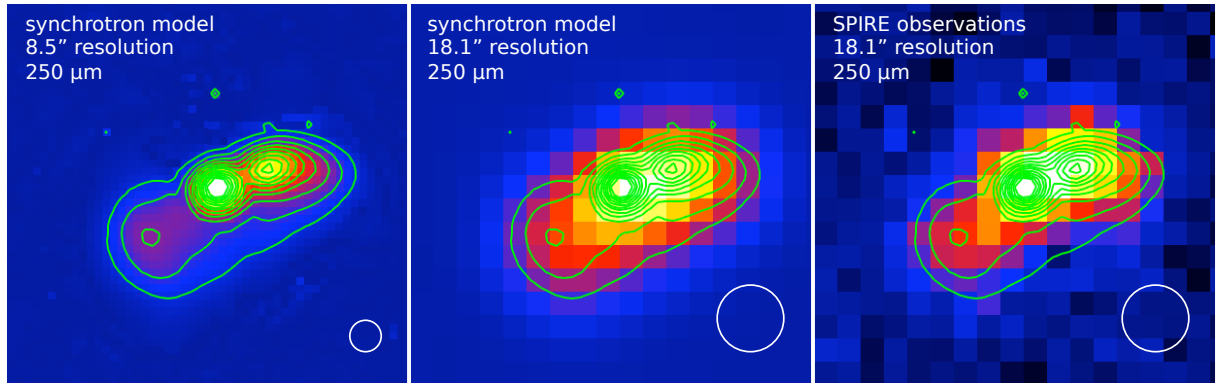


Figure 4.9: A comparison between the synchrotron model image and the observed image at $250\ \mu\text{m}$. *Left:* The synchrotron image at the model resolution ($8.5''$ FWHM, $2''$ pixels). *Middle:* The same model convolved to the SPIRE $250\ \mu\text{m}$ beam and pixel size ($18.1''$ FWHM, $6''$ pixels). *Right:* The observed SPIRE $250\ \mu\text{m}$ image. In all panels, the green lines are the contours of the synchrotron model at the model resolution (Baes et al. 2010a).

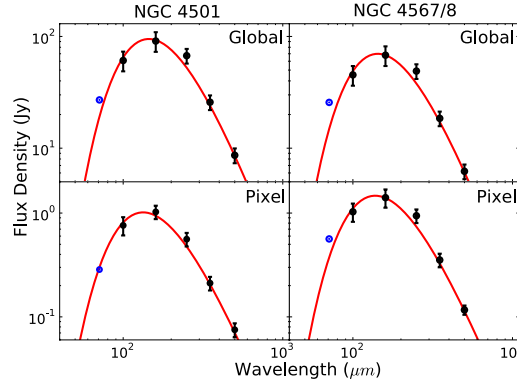


Figure 4.10: Global and example single pixel one component SED fits. If uncertainties are smaller than the symbol size, they are not shown. The 70 μm point (blue) is used as an upper limit (Smith et al. 2010).

4.5.2 Resolved dust analysis of spiral galaxies

Showcasing the HeViCS SDP field, a resolved dust analysis was carried out in Smith et al. (2010) for 3 spiral galaxies, NGC 4501 and the interacting system NGC 4567 & 4568, resulting in dust temperature, dust mass and gas-to-dust ratio maps through pixel-by-pixel SED fitting. Similar studies were previously limited by low S/N at wavelengths longer than 160 μm and had difficulty detecting the cold dust, resulting in a bias towards warmer dust temperatures and lower dust masses. With the PACS and SPIRE data points, both sides of the FIR peak in the SED (Figure 4.10) are sampled with better resolution and sensitivity.

As ancillary data, *Spitzer* 70 μm maps (Kennicutt et al. 2003; Struck et al. 2004; Kenney et al. 2006) were used, as well as *GALEX* FUV archival data, VLA HI maps (Chung et al. 2009), and Nobeyama CO($J=1-0$) maps for NGC 4501 (Kuno et al. 2007) and OVRO CO($J=1-0$) global fluxes for NGC 4567/8 (Iono et al. 2005). All images were convolved to the same resolution and astrometry as the SPIRE 500 μm maps.

The SED of each pixel in the resulting images was fitted in the 70–500 μm range with a simple modified black-body model $F_\nu = \frac{\kappa_\nu}{D^2} MB_\nu(T_d)$, where F_ν is the flux density at frequency ν , κ_ν the dust emissivity, D the distance to the galaxy (16.7 Mpc for all three, Mei et al. 2007), M the dust mass, and B_ν the Planck function at the dust temperature T_d . The dust emissivity is considered to follow a $\kappa_\nu \propto \nu^\beta$ power law in this range, with a value of $\kappa_0 = 0.192 \text{ m}^2 \text{ kg}^{-1}$ at 350 μm (Draine 2003a) and $\beta = 2$, although both values are notoriously uncertain. Taking the filter transmission into account, the chi-squared (χ^2) function was minimised to find the best fit.

The single component modified black-body fitted the 100–500 μm range data points well, but it showed a significant 70 μm flux excess for most pixels. An additional

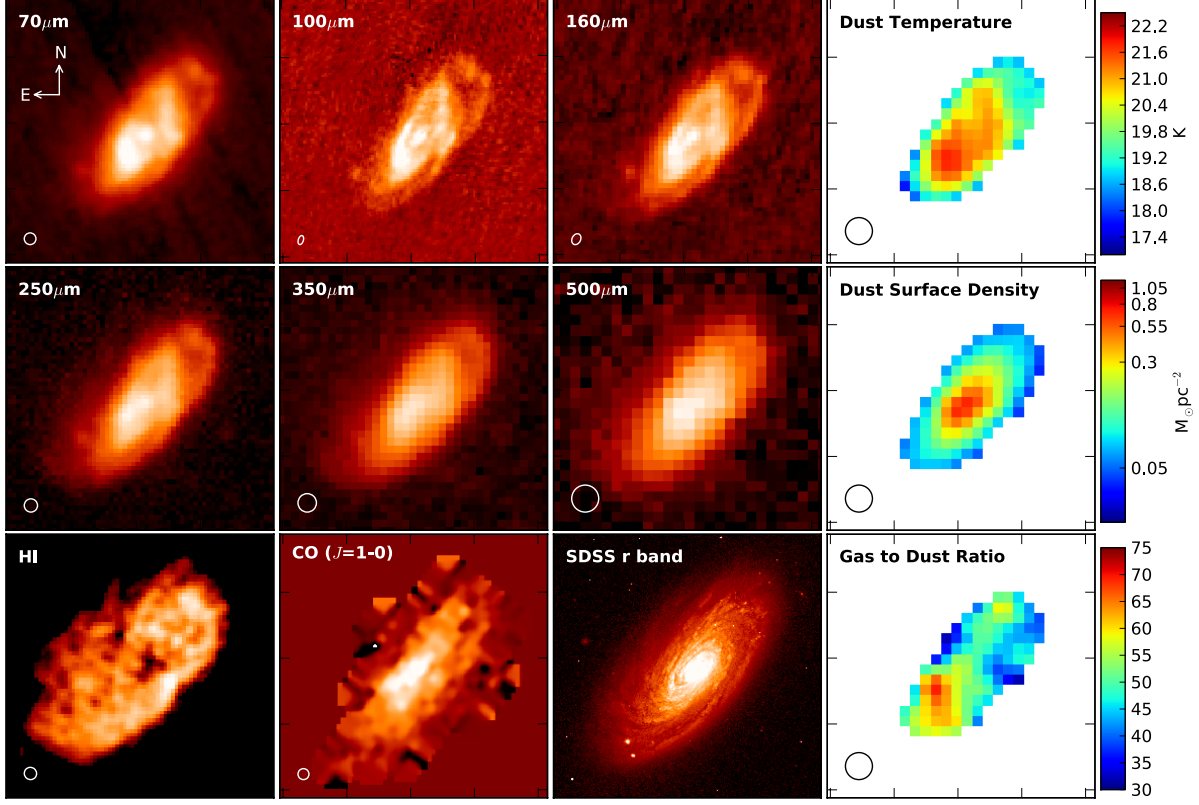


Figure 4.11: Images of NGC 4501 in their native resolution and pixel size, showing the MIPS 70 μm , PACS, SPIRE, and gas images on a log colour scale in the first three columns. On the right, maps of dust temperature, dust surface density (log scale), and gas-to-dust ratio are shown. The beam sizes for the respective wavelengths are indicated in the bottom-left corner of each panel. All panels are $6' \times 6'$ in size (Smith et al. 2010).

warmer dust component was checked to fit the latter data point as well, but this component is not tightly constrained, and the 70 μm data point was used as an upper limit instead. The parameter uncertainties were estimated with a bootstrap technique, yielding on average 1.0 K for the dust temperature and 23% for the dust surface density. These pixel-by-pixel fits then resulted in the dust temperature, dust mass surface density and gas-to-dust ratio maps (Figures 4.11 and 4.12).

These maps show a symmetrical dust mass distribution peaking at the galaxy centres and smoothly decreasing towards the outskirts by a factor of ~ 4 , consistent with the exponentially decreasing dust surface densities found in the SINGS sample (Muñoz-Mateos et al. 2009). The resulting global dust masses amount to $(1.2 \pm 0.3) \times 10^8 M_\odot$ for NGC 4501 and $(8.6 \pm 1.8) \times 10^7 M_\odot$ for NGC 4567/8, the latter split as $(1.7 \pm 0.4) \times 10^7 M_\odot$ and $(6.6 \pm 1.5) \times 10^7 M_\odot$ between NGC 4567 and NGC 4568, respectively. The dust temperature distributions have a more asymmetrical distribution, peaking at ~ 22 K in off-centre regions and falling down to ~ 19 K with increasing radius towards the outskirts. In all three galaxies, the global average dust temperature is 20 K.

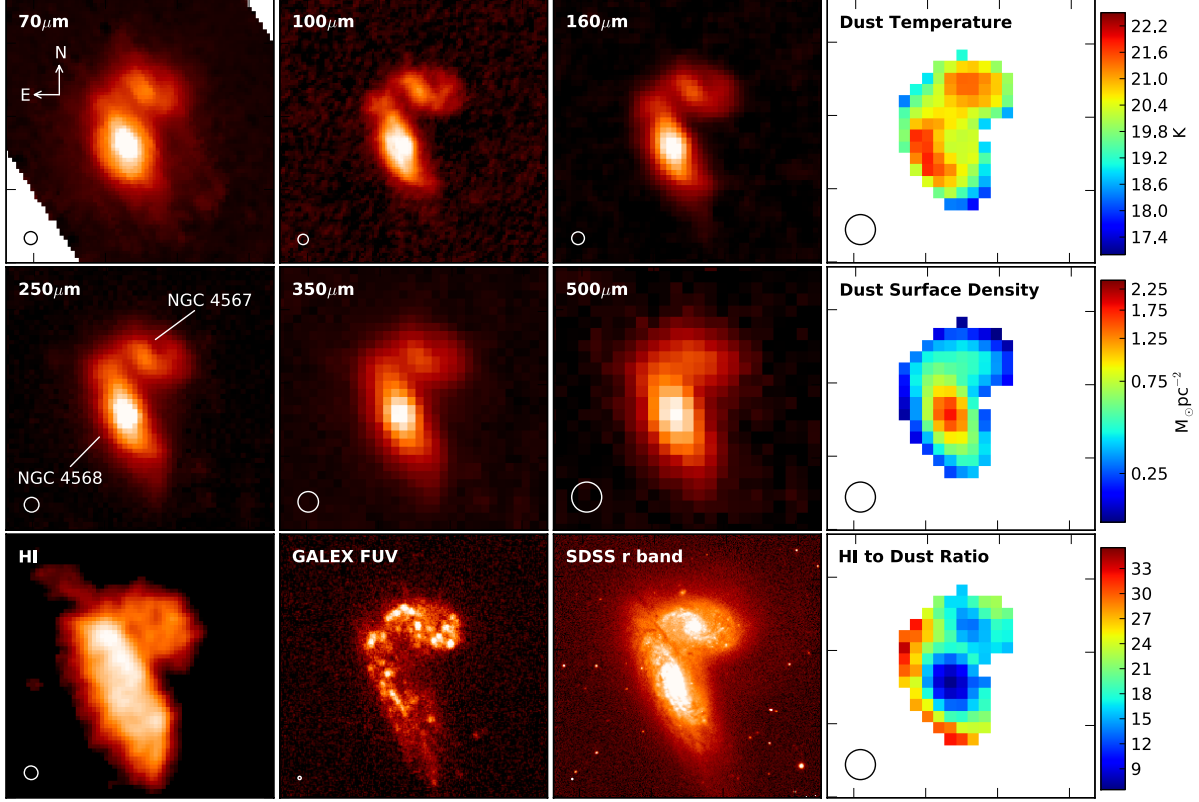


Figure 4.12: Same as Figure 4.11 but for NGC 4567/8 and with a GALEX FUV image instead of the CO($J=1-0$) map. The panels are $5.4' \times 5.4'$ in size (Smith et al. 2010).

The gas-to-dust ratio maps show an asymmetric distribution as well, for NGC 4501 peaking close to the dust temperature peak and varying across the galaxy by a factor ~ 2 . The pixel-by-pixel average value is 52 ± 13 , agreeing well with the global gas-to-dust ratio of 51 ± 14 . The low HI-to-dust ratio in the centre of NGC 4568 is likely due to denser molecular gas. The global neutral gas-to-dust ratios reach values of 32 ± 12 and 39 ± 14 for NGC 4567 and NGC 4568, respectively. All three ratios are low compared to the Galactic value of 100–200, but consistent with the lower end of the range in Draine et al. (2007). These low global gas-to-dust ratios could be caused by ram pressure stripping of the outer gas and dust discs, as NGC 4501 and NGC 4568 are slightly HI deficient (0.4–0.6, Chung et al. 2009).

4.5.3 Star-forming dwarf galaxies — dust in metal-poor environments

A sample of 3 star-forming Virgo cluster dwarf galaxies detected in the HeViCS SDP field were investigated in Grossi et al. (2010), portending the capabilities to study dust properties in low-metallicity environments with the full HeViCS observations. Previous MIR, FIR and sub-mm studies have turned up valuable insights about the various

Table 4.4: The properties of the three star-forming dwarf galaxies in the Virgo cluster under study: VCC number, absolute B magnitude, star formation rate, single modified black-body dust temperature and dust mass (Grossi et al. 2010).

ID	M_B (mag)	SFR ($M_\odot \text{ yr}^{-1}$)	$T_d^{1\text{BB}}$ (K)	$\log(M_d/M_\odot)$
VCC 562	16.74	4.6×10^{-2}	20.2 ± 0.2	5.18 ± 0.13
VCC 1179	15.46	9.4×10^{-2}	16.2 ± 0.6	5.48 ± 0.14
VCC 1356	16.15	4.6×10^{-2}	17.9 ± 1.1	5.53 ± 0.16

dust components in dwarfs, indicating even these metal-poor systems may contain a significant amount of dust (Thuan et al. 1999; Houck et al. 2004; Engelbracht et al. 2008), but mainly targeted isolated, bright dwarfs (Galliano et al. 2003; Hunt et al. 2005; Galliano et al. 2005; Galametz et al. 2009). The sub-mm excess emission noticed in some dwarfs (Madden 2002; Galliano et al. 2005; Galametz et al. 2009) may point to a very low temperature ($T \lesssim 10$ K) dust component, but this would require a high dust mass, thus raising different possible explanations (Lisenfeld et al. 2002; Bendo et al. 2010b, and references therein).

Even though dwarf ellipticals dominate the Virgo cluster dwarf galaxy population, about 10% of the dwarf galaxies are late-type dwarfs with indications of ongoing star formation (Binggeli et al. 1987). The three dwarfs in this case study are classified as blue compact dwarfs (BCDs, Binggeli et al. 1985), with basic parameters given in Table 4.4, assuming a distance of 16.5 Mpc (Mei et al. 2007). Their star formation rates, determined from extinction corrected $H\alpha$ and UV fluxes (Gavazzi et al. 2004; Boselli et al. 2009), are lower than what is typical for BCDs (Hunter & Elmegreen 2004; Zitrin et al. 2009).

The SDSS, *Herschel*/PACS and SPIRE images for these three dwarfs are shown in Figure 4.13; VCC 562 and VCC 1179 are not detected at $500 \mu\text{m}$ and $100 \mu\text{m}$ respectively. Single modified black-body fits to the *Herschel* SEDs (Figure 4.14, left panel), with a $\kappa_\nu \propto \nu^2$ emissivity law, were used to determine the dust temperatures in a similar way as in Smith et al. (2010), while the dust masses were constrained using the $250 \mu\text{m}$ flux densities and Li & Draine (2001). This results in values of between 16 and 20 K for the dust temperatures and several $10^5 M_\odot$ for the dust masses (Table 4.4).

For the two dwarfs detected at $500 \mu\text{m}$, an excess is obvious at this wavelength with respect to the fitted model. Several possible explanations for this difference have been suggested: thermal or non-thermal radio emission (Condon 1992; Hunt et al. 2005), an additional component of cold dust (~ 10 K, Galliano et al. 2003; Galametz et al. 2009), an enhanced small grain abundance (Lisenfeld et al. 2002), or amorphous dust

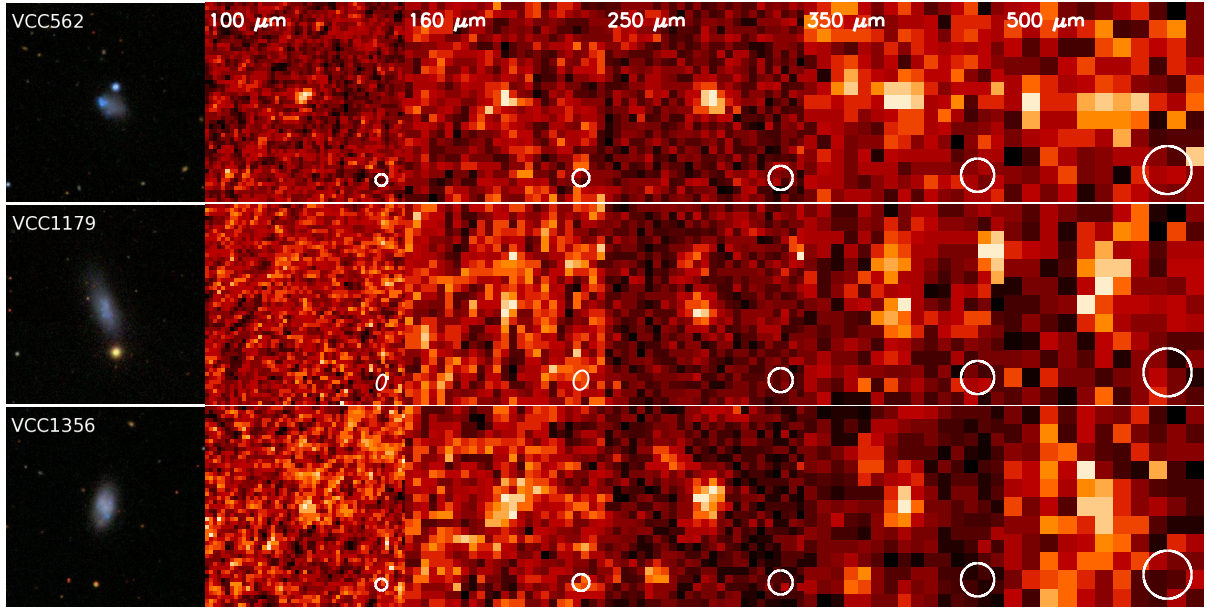


Figure 4.13: SDSS and *Herschel* images of VCC 562, VCC 1179, and VCC 1356 at 100, 160, 250, 350, and 500 μm . The field size is $150''$. The beam size FWHMs for each wavelength are displayed in the bottom-right corner of each panel, with ellipse and circle for single and cross-scan data, respectively (Grossi et al. 2010).

grains with different optical properties (Meny et al. 2007). Due to the low SFR in these BCDs ($\lesssim 10^{-1} M_{\odot} \text{ yr}^{-1}$), the total expected thermal and non-thermal radio emission (Condon 1992) of around 200 μJy at 500 μm is insufficient to explain this excess.

In the absence of a 100 μm data point and the large uncertainties on the flux densities, a fit with a second, cold dust component to the VCC 1179 data was poorly constrained and this possibility was only investigated further for VCC 1356. The resulting fit, with mean temperatures $T_c = 8 \text{ K}$ and $T_w = 19.1 \text{ K}$ for the colder and warmer dust components respectively, is displayed in the right panel of Figure 4.14. The total dust mass for this case is $M_d = 1.6 \times 10^7 M_{\odot}$, but several sets of parameters give reasonable fits to the data, the one with the least cold dust component ($T_c = 11 \text{ K}$ and $T_w = 19.6 \text{ K}$) having a total dust mass of $M_d = 2 \times 10^6 M_{\odot}$, still six times the value for a single dust component. Overall, the limited data from the SDP made it difficult to discriminate between the different scenarios for the 500 μm excess.

4.5.4 The Bright Galaxy Sample

The sample selection for the Bright Galaxy Sample (Davies et al. 2012) was previously discussed in Section 4.4. The aperture photometry results based on the single cross-scan data for these 78 bright Virgo Cluster galaxies are catalogued (Davies et al. 2012, Table 1) with identifications, coordinates, velocities, distances and measured *Herschel*

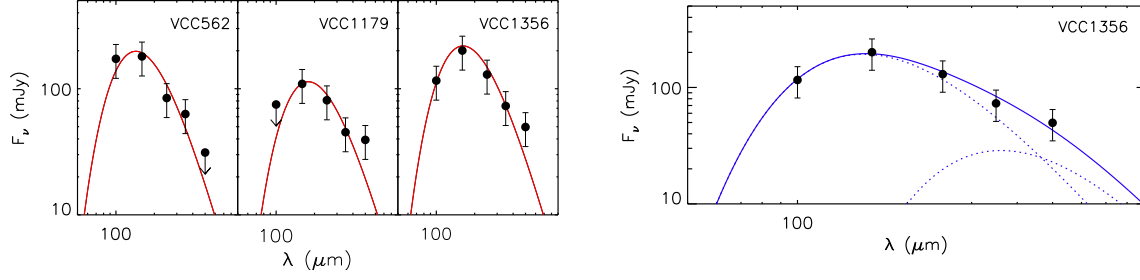


Figure 4.14: *Left:* Single modified black-body fits, with emissivity index $\beta = 2$, to the *Herschel* SEDs of the VCC dwarfs. *Right:* A two-component model fit with $\beta = 2$, $T_w = 19.1$ K, $T_c = 8$ K for VCC 1356 (Grossi et al. 2010).

flux values for each band, without including colour corrections. The velocities and distances were taken from GOLDMINE, while the coordinates were determined by centroiding the $500 \mu\text{m}$ data.

Luminosity function and distributions

The Virgo bright galaxy luminosity function and distributions⁴, which give the total number of galaxies within each luminosity interval, are shown for each *Herschel* wavelength in Figure 4.15. The shape of these luminosity distributions can be compared with those obtained for galaxies in other environments to assess the influence of that particular environment (field or varying richness of group or cluster) and at different redshifts to assess evolution over cosmic time. Given the proximity of Virgo, and hence the detail and depth of the observations, this Bright Galaxy Sample is expected to act as a benchmark for future studies.

The obtained FIR luminosity function/distributions are quite different from those in the optical. The latter include large numbers of low luminosity galaxies found in the cluster, giving rise to a reasonably good Schechter function fit with faint end slope of the order -1.3 to -1.6 (Sabatini et al. 2003). The FIR luminosity function/distributions for the Bright Galaxy Sample all turn over at faint luminosities.

Due to selection effects, galaxies with large enough luminosities but which are too small at the chosen isophote, will not be part of the sample. However, there are a few indications that the FIR luminosity function/distributions in Figure 4.15 are rather accurate:

1. Even the faintest galaxies in the sample have a minimum S/N of 15, i.e. the last point of the $500 \mu\text{m}$ luminosity function is not adversely affected by a S/N limit.

⁴ The term luminosity function is used to refer to the $500 \mu\text{m}$ data because the data is selected at this wavelength. The term luminosity distribution refers to data at other wavelengths.

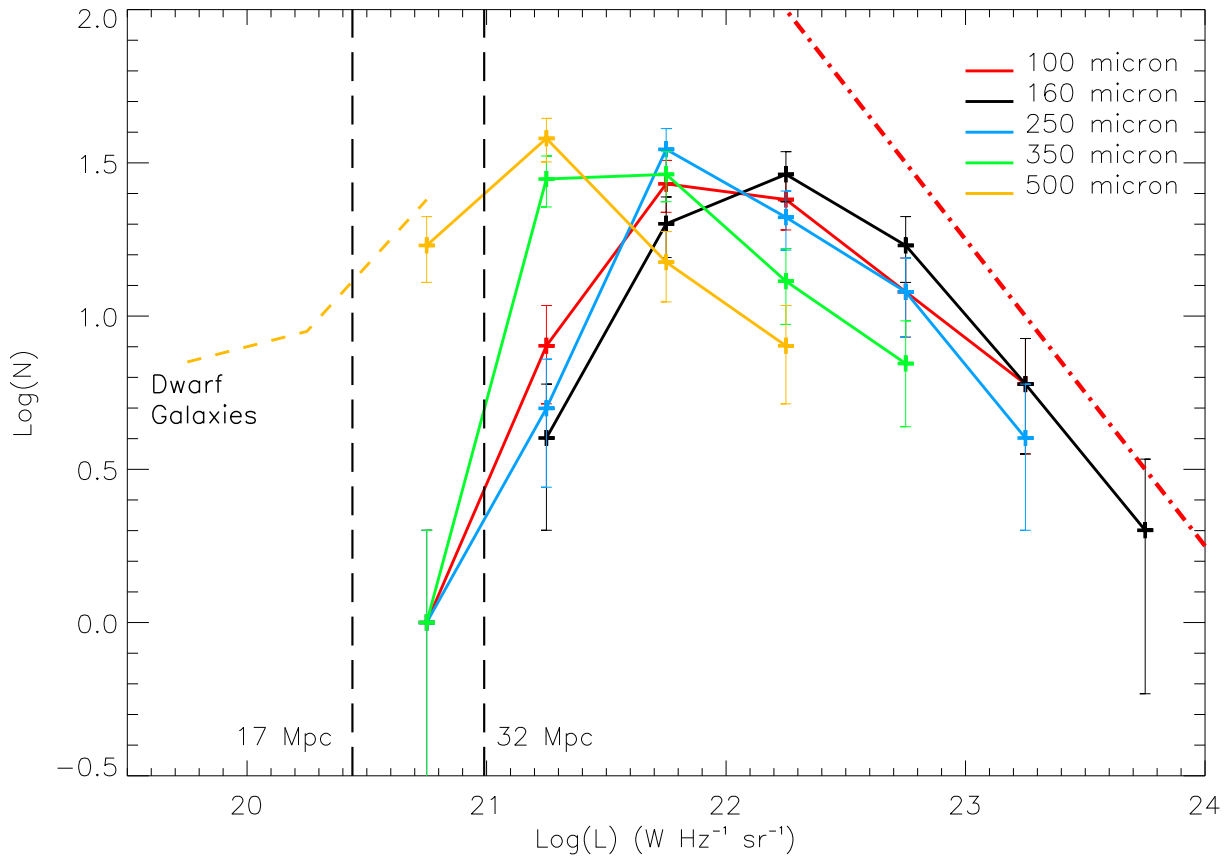


Figure 4.15: The luminosity distributions derived from the Virgo Bright Galaxy Sample catalogue. The red dot-dashed line indicates a slope of -1 as found by Rowan-Robinson et al. (1987) using *IRAS* 100 μm data. The vertical black dashed lines indicate the minimum luminosity at 17 and 32 Mpc for a minimum 500 μm flux density of 0.1 Jy. The yellow dashed line indicates the shape of the 500 μm luminosity function if known star-forming dwarf galaxies, beyond the detection limit, are included (Davies et al. 2012).

2. In Davies et al. (2010) we showed that the luminosity function/distributions are peaked independent of the wavelength (e.g. 160 μm) used for selection.
3. At optical wavelengths Sandage et al. (1985) found that the luminosity distributions of Virgo cluster bright spiral and elliptical galaxies (analogous to this sample) were Gaussian and only became power laws (Schechter functions) when the dwarf galaxies were included. These dwarf galaxies are predominantly metal-poor dE galaxies and it was previously shown that these are not detected at 500 μm in the data used for this sample (De Looze et al. 2010).
4. A total of 24 out of 139 late type dwarf galaxies listed in the VCC with a measurable 500 μm flux but too small to be included in the sample, have been identified (Grossi et al. 2010; Grossi, communication to the HeViCS consortium). These 24 galaxies have been added to the 500 μm data shown in Figure 4.15 (yellow dashed line) but do not alter the conclusion about a 'peaked' luminosity function.

Table 4.5: The mean luminosity in each band for the Virgo Bright Galaxy Sample. The temperatures are those that produce modified black-body curves that peak in each band, with $\beta = 2$ (Davies et al. 2012).

Band (μm)	Mean luminosity $\times 10^{22}$ ($\text{W Hz}^{-1} \text{sr}^{-1}$)	Temperature (K)
100	3.4 ± 0.6	20.2
160	4.4 ± 0.8	12.6
250	2.4 ± 0.4	8.1
350	1.0 ± 0.2	5.8
500	0.4 ± 0.1	4.0

FIR sources without optical counterparts could exist, but they have to be cluster members and not associated with faint optical sources in the background. No such objects were noticed in the VCC based sample. If indeed confirmed, the ‘peaked’ nature is similar to the apparent turnover at low masses in the Virgo cluster HI mass function (Davies et al. 2004), which differs from the low-mass power-law slope of the global HI mass function (Martin et al. 2010; Davies et al. 2011). The straightforward explanation for this is that gas stripping processes (Doyon & Joseph 1989) in the cluster are more dramatic for low-mass galaxies. Figure 4.15 would suggest this may now also apply to the removal of cosmic dust, but the fate of stripped galactic dust is still unclear.

Due to the limited availability of similar luminosity distributions (see Davies et al. 2010), the most informative comparison is with the *IRAS* 100 μm luminosity function derived by Rowan-Robinson et al. (1987). They constructed a FIR sample from optically identified galaxies with an available redshift in a similar way to the Bright Galaxy Sample, but their sample is drawn from a wide range of environments. Their luminosity function follows a power law slope of about -1 from $\sim 10^{24}$ to $\sim 4 \times 10^{21} \text{ W Hz}^{-1} \text{sr}^{-1}$. Although its normalisation is arbitrary compared to the BGS data (Figure 4.15), it is clear that their luminosity function predicts $\sim 10^3$ more galaxies at the faint end than at the bright end — even with the small numbers in the Bright Galaxy Sample, this is difficult to reconcile with the HeViCS data. The *IRAS* 100 μm data also includes galaxies one order of magnitude brighter than the brightest galaxies found in the Virgo cluster — it has previously been noted that clusters in general do not have the very bright FIR sources seen in the field (Bicay & Giovanelli 1987).

Given the apparent shape of the Virgo cluster luminosity function/distributions, it is currently more informative to simply characterise them by their mean values rather than a poorly fitted and parametrised Schechter function. These mean values are given in Table 4.5. It is clear that the majority of the FIR energy of the cluster is being pro-

Table 4.6: Colour corrections for a $\beta = 2$ modified black-body of temperature T . Pipeline fluxes (i.e. calibrated assuming $\nu F_\nu = \text{constant}$) should be multiplied by these factors to retrieve corrected fluxes. For the SPIRE bands, the regular values are for extended sources, while those within parentheses are for point sources (Davies et al. 2012).

T (K)	100 μm	160 μm	250 μm	350 μm	500 μm
15	0.96	1.06	1.00 (0.98)	0.99 (0.96)	0.99 (0.92)
20	1.03	1.03	0.99 (0.96)	0.98 (0.94)	0.98 (0.90)
25	1.03	0.99	0.08 (0.94)	0.97 (0.93)	0.97 (0.88)

duced at the shortest of these wavelengths. Wien’s law for the predicted temperature of a modified black-body curve with emissivity β , i.e. $T_d \approx \frac{14142.9}{(5+\beta)\lambda_{\text{max}}}$, leads to the temperatures given in Table 4.5 for each wavelength (band) λ_{max} and emissivity $\beta = 2$. Clearly dust temperatures of the order 13-20 K (see below) are expected from this.

Dust temperatures and masses

In order to derive the dust temperatures and masses, the SEDs for each galaxy, as defined by the *Herschel* flux densities in the BGS catalogue, were fitted with a single-temperature modified black-body function. The same procedure adopted in Smith et al. (2010); Bendo et al. (2010a) and Magrini et al. (2011) was followed (see this later work for a discussion of the uncertainties when using a single-temperature model).

A power-law dust emissivity $\kappa_\lambda = \kappa_0(\lambda_0/\lambda)^\beta$ was adopted, with spectral index $\beta = 2$ and emissivity $\kappa_0 = 0.192 \text{ m}^2 \text{ kg}^{-1}$ at $\lambda_0 = 350 \mu\text{m}$. The fit was obtained with a standard χ^2 minimisation technique, first applying the colour corrections stated in Table 4.6 to the measured flux values of the BGS catalogue.

The majority of galaxies in the BGS catalogue are simply and well fitted by this single-temperature (modified) black-body curve; the fits are illustrated in Figure 4.16 (ordered by χ^2 value). There are three notable exceptions to this. The early-type galaxies NGC 4486 (M 87) and NGC 4374 (M 84) show departures from a thermal spectrum (Boselli et al. 2010a), particularly at longer wavelengths. As discussed specifically for NGC 4486 in Baes et al. (2010a) and earlier in Section 4.5.1, both these galaxies require modelling of the synchrotron component and its removal before the thermal dust spectrum can be analysed. The third galaxy, NGC 4378, is an early-type spiral with a Seyfert nucleus. Its SED does not appear to be contaminated by a non-thermal contribution, but rather dominated by a colder dust component, because its 160 μm flux is lower

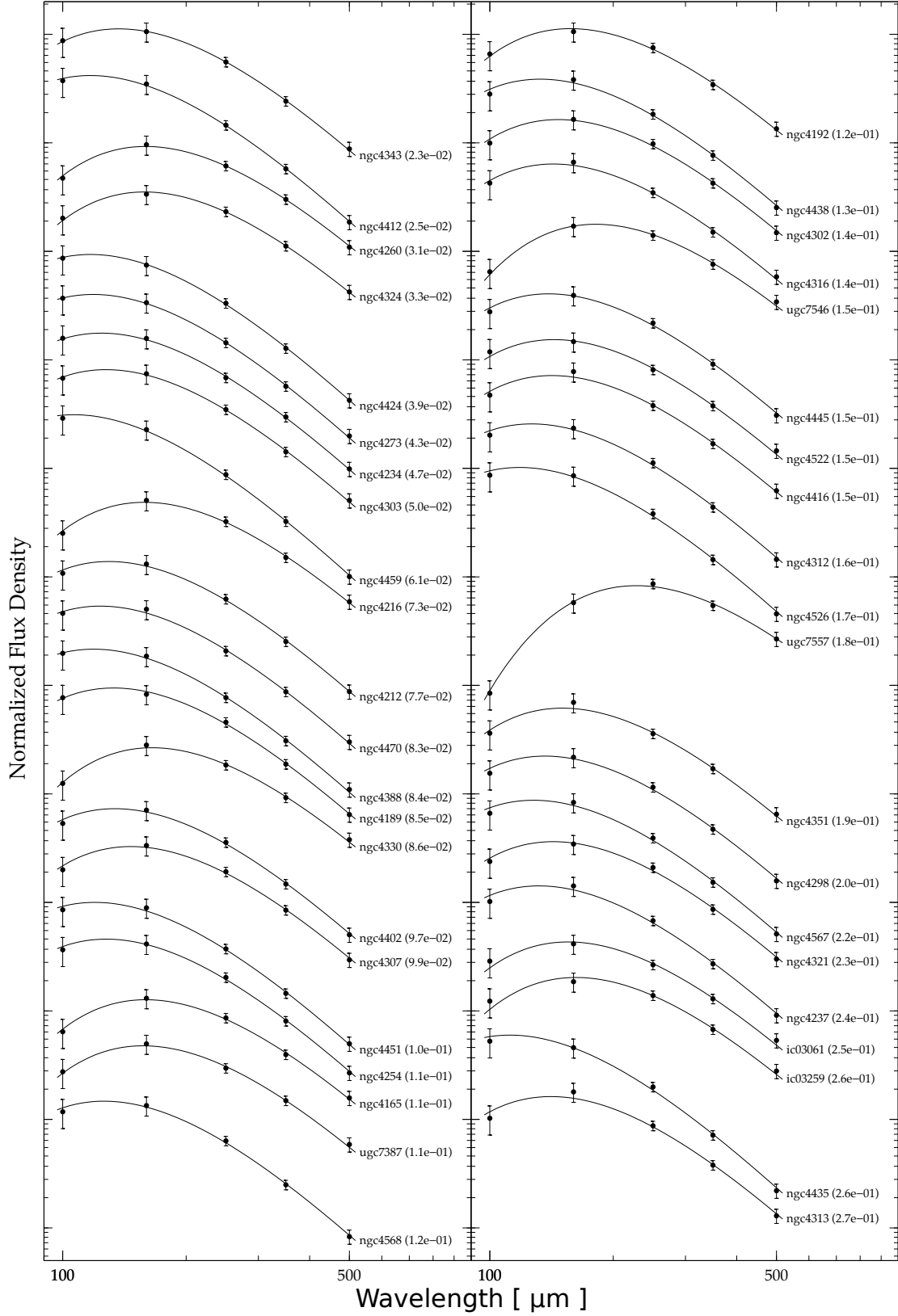


Figure 4.16: The spectral energy distributions of the Bright Galaxy Sample and modified black-body fits ordered by reduced χ^2 value (given in parenthesis). Three galaxies that are not well fitted by a modified black-body are shown using a dashed line (Davies et al. 2012).

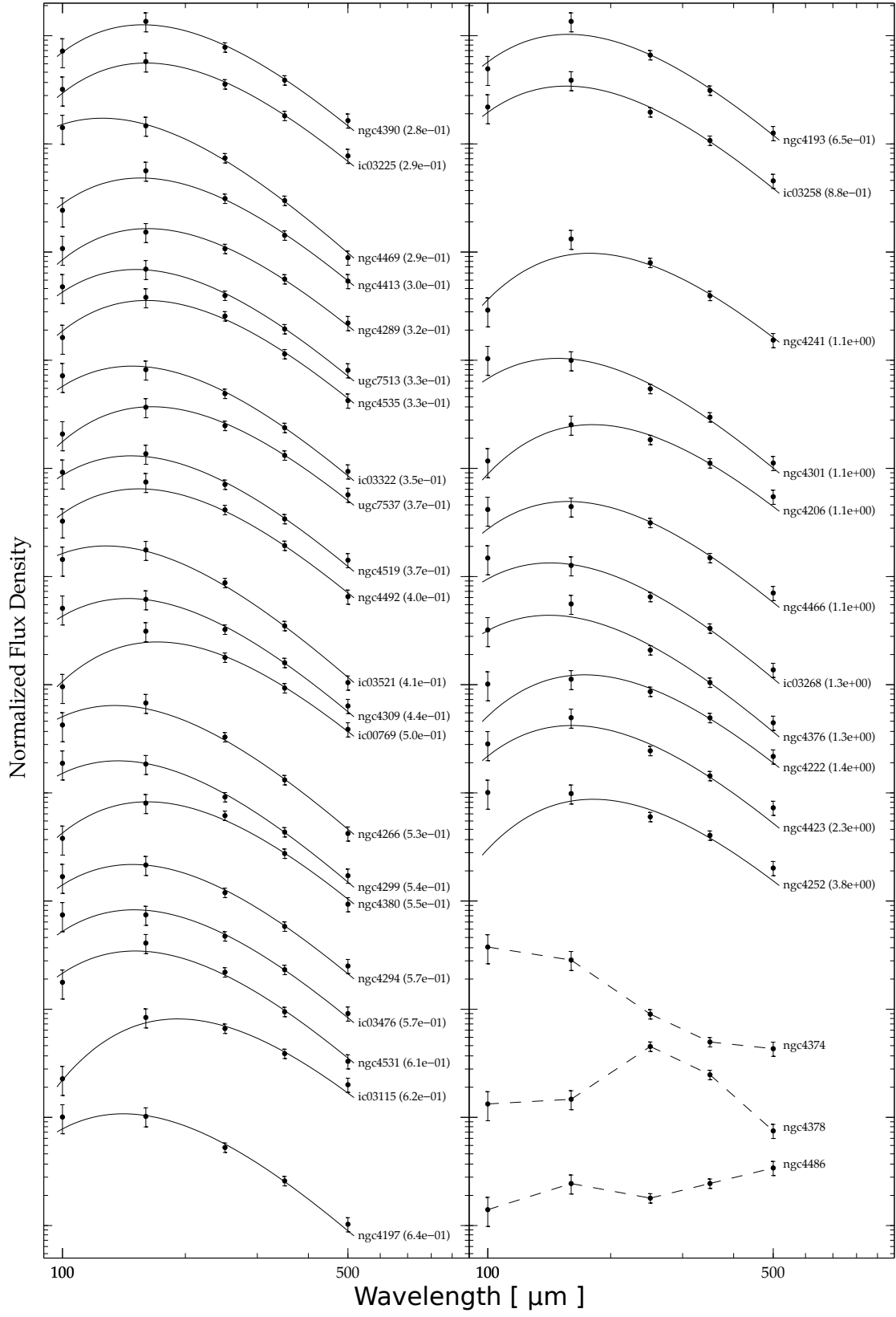


Figure 4.16: *continued*

than expected when compared to the other values. It requires more detailed radiative transfer modelling and probably a multi-component dust model before a substantial cold dust component is confirmed.

Derived dust masses and temperatures (for the 75 galaxies with a reliable fit) are in the range of $10^{6.22-8.17} M_{\odot}$ and 12.8–27.2 K respectively, with mean values of $10^{7.31} M_{\odot}$ and 20.0 K (Davies et al. 2012, Table 4). This illustrates the potential sensitivity of the full depth survey to low dust masses ($<10^6 M_{\odot}$) and the existence of a significant cold dust component ($T < 20$ K). Calculated galaxy dust masses and temperatures from surveys similar to HeViCS were typically $10^{6.6} M_{\odot}$ and 30–50 K (taken from Soifer et al. 1987, where they have 31 galaxies in common with HeViCS; see also Devereux & Young 1990). The typical dust mass is now almost an order of magnitude higher and the temperature almost 20 K colder (see also Tuffs et al. 2002).

Interestingly, the coldest galaxy in the sample (12.8 K) is UGC 7557, the galaxy with the most discrepant *IRAS* 100 μm flux (Figures 4.4 and 4.16). It is barely detected in the PACS 100 μm data, but is relatively strongly detected in the other bands. The data provide a reasonably good fit to a modified black-body curve with a calculated dust mass of $10^{7.42} M_{\odot}$. UGC 7557 is classified as a Scd galaxy and appears to be of rather low surface brightness in the optical. Compared to the other galaxies in this sample, it is also a little underluminous in the optical with a *B*-band absolute magnitude of -18.5 . If the FIR emission is from very cold dust then its origin is unclear. Being apparently of low surface brightness, the dust may just be further away from the stars. Alternatively, the dust in this low-luminosity galaxy may have a different emissivity and/or size distribution. The complete distribution of dust temperatures is shown in Figure 4.17.

4.6 Identification of serendipitously observed asteroids in HeViCS

The scientific objectives are clearly extragalactic in nature. However, the Virgo Cluster is named after the Virgo constellation it is mainly located in. This constellation is part of the zodiac and lies on the ecliptic. Therefore it is obvious that from time to time, a Solar System object crosses the fields of the survey. During the scheduling of observations, the major planets are generally avoided because of their high brightness, which may cause the detector arrays to saturate. But minor planets are a different case: there are too many to avoid, so once in a while, one can traverse the observation field where it can be picked up by the detectors during a scan.

Indeed, in a number of HeViCS fields a relatively bright object was noticed with a clearly shifting position between scan orientations, in most cases with different posi-

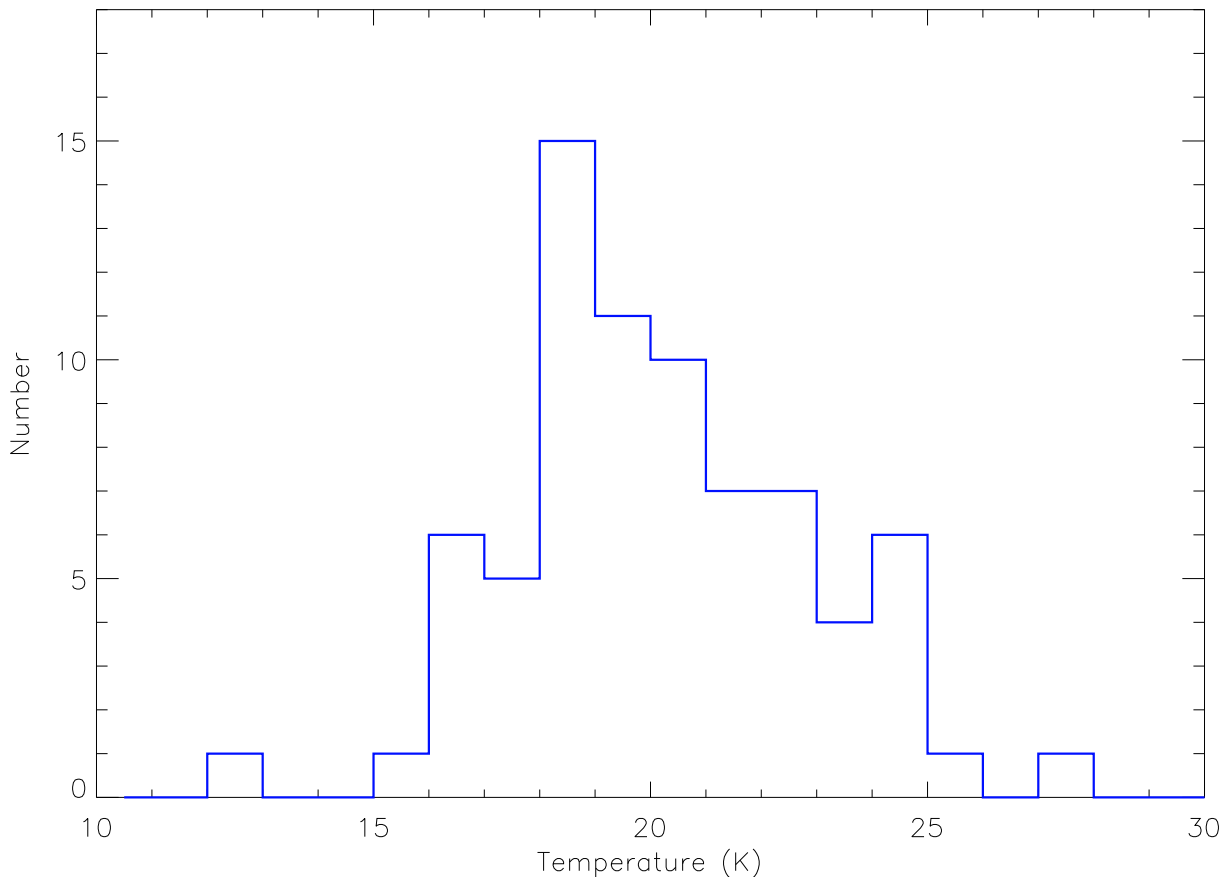


Figure 4.17: The distribution of global average dust temperatures (Davies et al. 2012).

tions in the PACS and SPIRE maps, due to the focal plane offset between both instruments. For some, a map with the difference between maps for the different scan directions was necessary to bring them out more clearly, while others were easily found in the error maps (Figure 4.18). Normally, these objects can be identified using the minor planet database interface MPCChecker provided by the IAU Minor Planet Center⁵, but the space-based *Herschel Space Observatory* has no observatory code. To circumvent this problem, we provided the coordinates of the object and a date value roughly corresponding to the halfway point for that scan observation and chose geocentric coordinates using the observatory code 500. To account for difference between the actual coordinates from *Herschel's* point of view and these geocentric coordinates, as well as the uncertain estimate of the observing time, the search aperture size needs to be set rather large. This usually produces a list of a few candidate objects.

To discriminate between the different possibilities, we used the HORIZONS ephemeris service web interface⁶ (Giorgini et al. 1996), developed and maintained by the Solar System Dynamics Group at the Jet Propulsion Laboratory (JPL). This does have an

⁵ <http://www.minorplanetcenter.net/iau/mpc.html>

⁶ <http://ssd.jpl.nasa.gov/horizons.cgi>

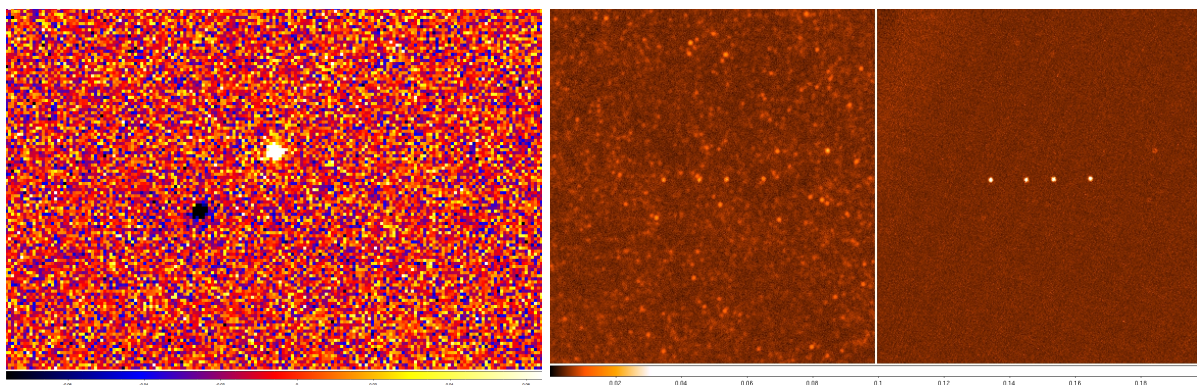


Figure 4.18: *Left:* A difference map showing the movement of (776) Berbericia between a nominal and an orthogonal scan with a positive and a negative image. *Right:* Four scans taken in quick succession picked up (128) Nemesis, barely noticeable in the regular SPIRE 250 map (*left half*), but clearly standing out in the error map (*right half*).

observatory code for *Herschel* (500@-486), and using the time interval of the observation as the time span, we generated ephemeris tables from *Herschel*'s viewpoint for each of the possible target bodies. Plotting the sky coordinates of these orbits together with the actual positions of the detections, shown in Figure 4.19, then made it easy to identify each of the asteroids (Verstappen et al., in preparation).

With the observation dates of the different scans, all possible asteroids crossing the fields could be retrieved from MPCChecker to confirm whether or not they are observed. The orbits could then indicate the exact time this should happen for each instrument and the individual frames located in the timeline. The detections are useful to characterise the PSFs and to determine the astrometric offsets by comparing the actual with the expected locations. They can also be used for flux calibration, or verification of models predicting the FIR emission of these asteroids. With reasonable assumptions about the emissivity and using the known distance, various physical properties such as mass, radius and possibly rotational axes could also be estimated, although e.g. the latter would require a multitude of observations to generate a light curve, which is not possible with only unintended sightings.

4.7 An extension: the *Herschel* Fornax Cluster Survey (HeFoCS)

For the second Open Time call (OT2), a similar proposal to the *Herschel* Virgo Cluster Survey was submitted and shortly after approved, to observe the second nearest galaxy cluster, the Fornax cluster, with *Herschel* (*Herschel* Fornax Cluster Survey (HeFoCS), Davies et al. 2013). This particular cluster is less populous than the Virgo cluster, containing about 350 catalogued galaxies (Fornax Cluster Catalogue (FCC),

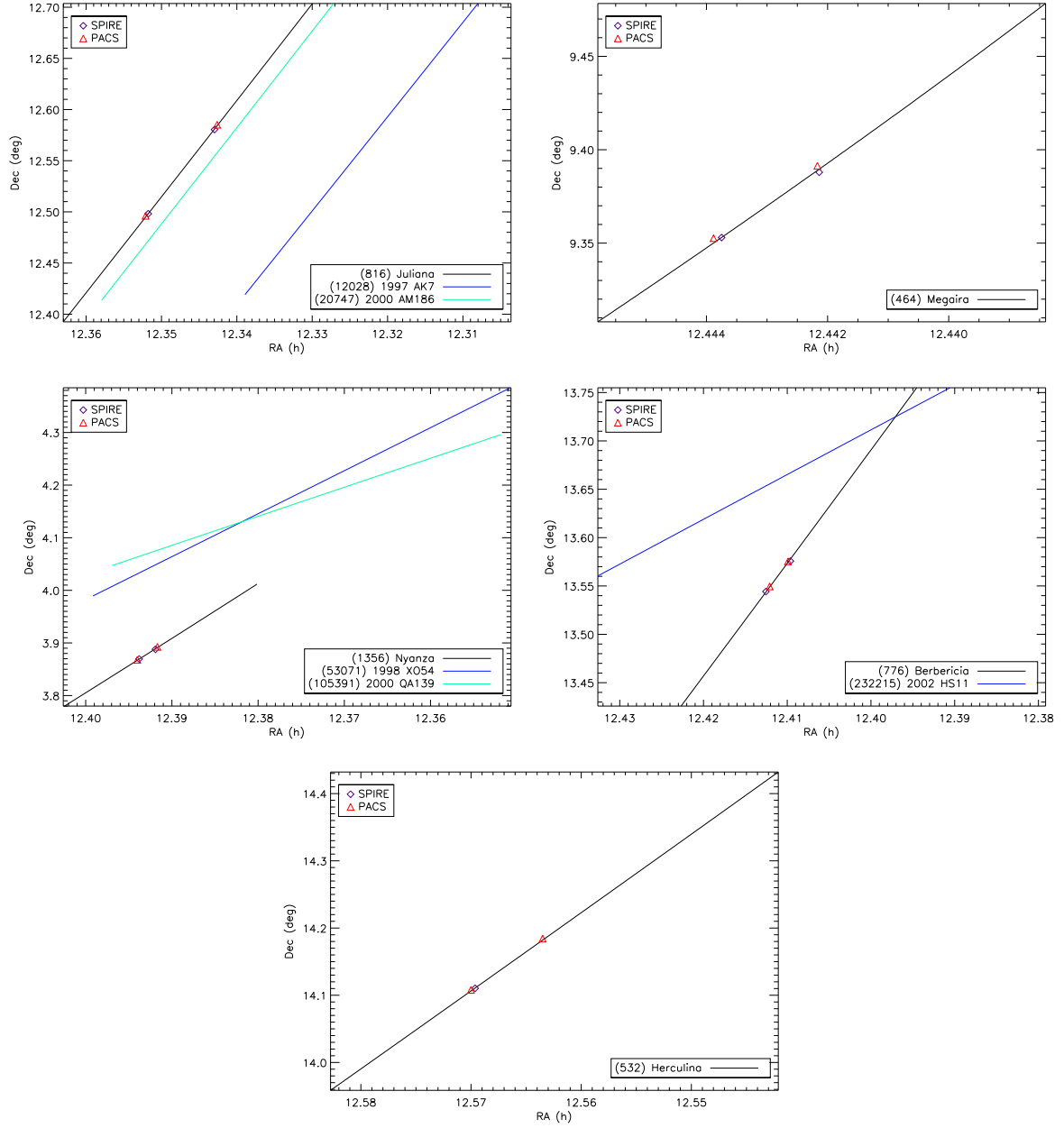


Figure 4.19: Comparison of the orbits for different possible minor planets with the actual positions of detections renders identification almost trivial.

Ferguson 1989). Its mean velocity is 1493 km s^{-1} , implying Fornax lies at a distance of about 19.3 Mpc, only 1.2 times further away than Virgo (Jordán et al. 2007). Fornax has a velocity dispersion of about 374 km s^{-1} and a core radius of 0.7° (250 kpc at the Fornax distance), which gives a mass of $\sim 7 \times 10^{13} M_\odot$, about a factor seven less than Virgo (Jordán et al. 2007).

Although less massive, the central galaxy number density is about two times higher in Fornax than in Virgo and with the lower velocity dispersion, it is expected to have more influential galactic tidal interactions. The galaxies in the Fornax cluster may therefore have a quite different gas accretion and stripping history, more typical of the groups and poor clusters where most galaxies reside in. Fornax also contains large quantities of X-ray emitting gas, but it is quite centralised around the central dominant elliptical galaxy NGC 1399 (Paolillo et al. 2002; Scharf et al. 2005). Like Virgo, Fornax does show clear evidence for substructure indicating its current and continuing assembly (Drinkwater et al. 2001), though it is more regular in shape and probably more dynamically evolved than Virgo. Part of the substructure is centred on the unique nearby radio source Fornax A (NGC 1316) which has a dust enshrouded AGN and radio lobes extending almost a degree across the sky (Bland-Hawthorn et al. 1995).

The scientific objectives for this survey are essentially the same as for HeViCS, described in Section 4.2. The observing strategy is also very similar, in that the sensitivity should reach the confusion limit for SPIRE at $250 \mu\text{m}$ ($\sim 1 \text{ MJy sr}^{-1}$) to allow for the detection of faint emission from intra-cluster dust. As the confusion noise for this area of the sky is different, only 4 fast speed scans ($60''/\text{s}$) are required, using both PACS and SPIRE in parallel. The original proposal asked for 3 fields measuring $231' \times 231'$ each, requiring a total of 93 hours, but since just a third of this was awarded, only a central field was effectively observed.

In this Chapter, a wide area proposal to observe the large local galaxy M31, carried out with *Herschel*, is presented in Section 5.1. The observations and the PACS data reduction are discussed in Section 5.2. In Section 5.3, we deduce some global and large scale properties of the dust in this galaxy (covering parts of Fritz et al. 2012), and we conclude with some finishing remarks on these results in Section 5.4.

Similarly as for the HeViCS programme (Chapter 4), the UGent group was responsible for reducing the PACS data and producing its final maps. On top of this, I was personally in charge of designing the fields to be observed, as well as other technical details of the observations. We should also point out that these observations were selected by ESA to be used as a showcase of *Herschel*'s capabilities, presenting our first maps in a BBC programme just two weeks after they were taken. This has led to a number of press releases, giving exposure to our group on national radio, local television, in a national news magazine and on the BBC website.

5.1

Observing the Andromeda Galaxy with *Herschel*

Taking advantage of *Herschel*'s excellent sensitivity and resolution, a Guaranteed Time proposal to observe the extensive surroundings of the Andromeda galaxy in Parallel Mode with PACS and SPIRE was submitted and approved. Andromeda, or M31, is the closest large galaxy, and in many aspects, it can be considered a twin of our own Milky Way. The size of the observation field is $\sim 5.5^\circ \times 2.5^\circ$, about five times larger than any previous IR map of M31, which usually covered the central $\sim 3^\circ \times 1^\circ$ field (e.g. Barmby et al. 2006; Gordon et al. 2006). Moreover, the proposal formed a first in that M31 was never before observed at the wavelengths covered by the SPIRE instrument.

The first stated objective of the proposal was an investigation of the relation between the dust and the radiation field within Andromeda. The SPIRE data should make it possible to detect whether an extra cold dust component ($\lesssim 10$ K) exists beyond the already known cold (~ 16 K) and warm (~ 45 K) dust components (Haas et al. 1998). The combination of the great variety of archival data on M31, more specifically those maps

at wavelengths covering the UV-to-NIR SED, with PACS images should allow to make the distinction between obscured star formation regions and regions where the diffuse radiation field dominates the heating of the dust. This information is invaluable to accurately measure quantities such as star formation rates and dust attenuation.

Another goal of the observing programme is tracing the dust emission beyond the already known structure of a barred nucleus, two spiral arms and a dusty, star-forming ring. Using radio data, these extended structures could then be linked to atomic and molecular gas. Since the large field also covers M 31's two major satellites, their dust contents can be further investigated as well. A third aim is to research the spatial variation of the gas-to-dust ratio, taking into account the dust characteristics such as temperature and chemical composition, which are crucial in determining this ratio (Montalto et al. 2009). The results can then be used to find the dust abundances in similar, more distant and unresolved, spiral galaxies.

The design of the Astronomical Observation Request (AOR) was rather intricate, since the desired field rather elongated. It is actually longer than the maximum allowed width, making it impossible to observe with only one nominal and one orthogonal scan. Therefore the field had to be split into two separate slightly overlapping cross-scans. As the known coordinates of M 31 were thus no longer applicable to set the field centres, new central points were calculated, lying along the extent of the major axis. When these new centres were determined, the generally adopted major axis position angle of 38° (Hubble 1929, giving a 36.7° value; Lindblad 1956, implying 39° ; de Vaucouleurs 1958, $37.7^\circ \pm 0.2^\circ$; Peterson et al. 1977; Montalto et al. 2009) was used.

An extra requirement was that both smaller fields do not exceed the allocated observing time. Another condition was that they overlapped along the minor axis, covering an overlap of at least several arcminutes, but not as much so that the extreme edges of the map, where any emission can be considered to be faint at best, would be sacrificed for the sake of a larger area with double coverage around the centre, which is bright anyway. Since the fields rotate as the visibility window progresses, a further investigation was carried out to put a timing constraint on the observations to limit the relative angle between the fields (Figure 5.1). It was decided to end the constrained observation windows ~ 2 weeks after the start of the available visibility periods, with a stated preference to observe both cross-scans as close in time to each other as possible.

Throughout all works within the HELGA project, we will assume a distance to Andromeda of 785 kpc (McConnachie et al. 2005), which translates into a linear scale of $3.8 \text{ pc}''$. As for the inclination and position angles, we are using $i = 77^\circ$ and $\text{PA} = 38^\circ$, respectively. In Fritz et al. (2012), the data reduction and the *Herschel* maps are presented and the global FIR and sub-mm morphology is described, making a compari-

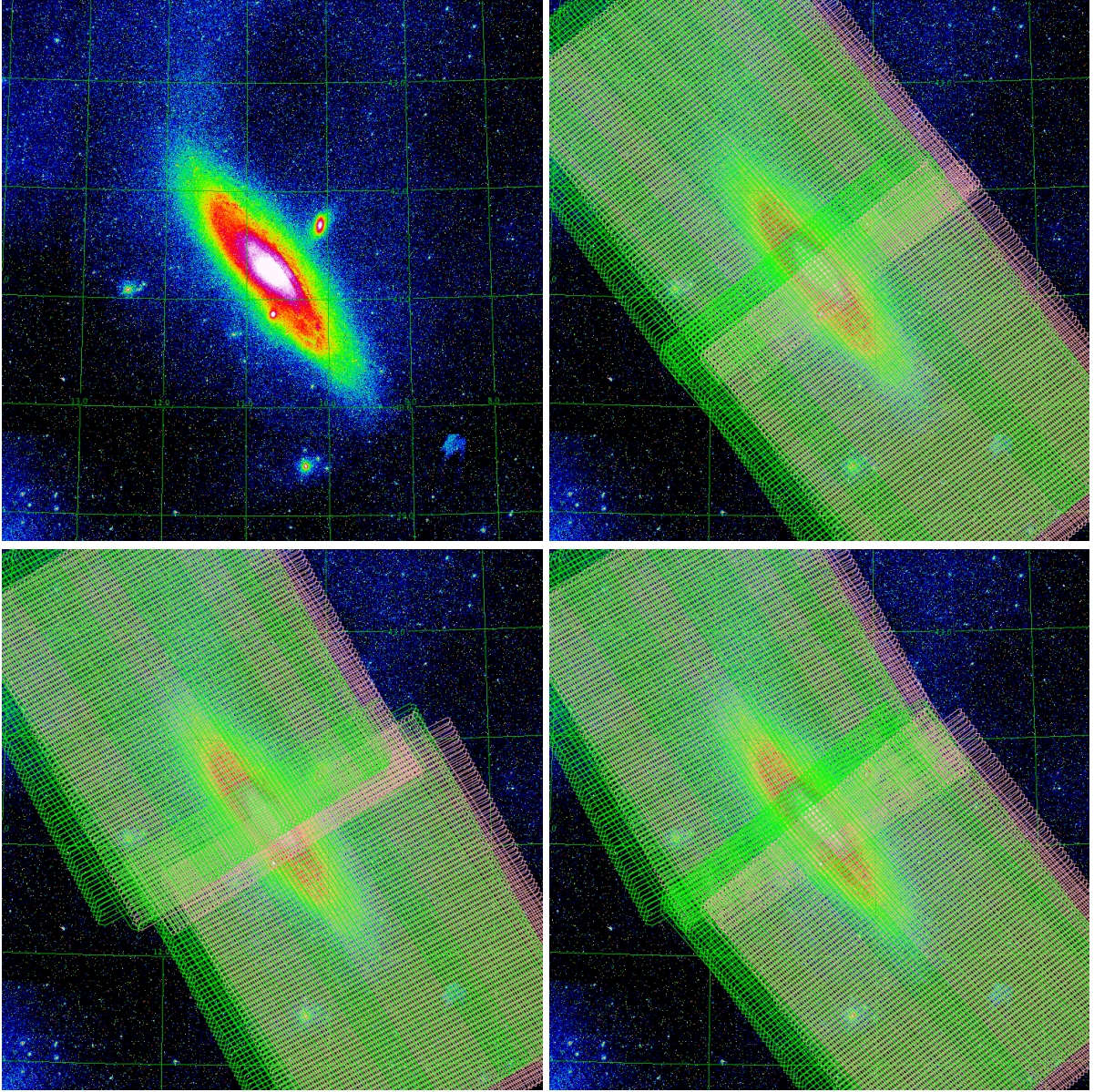


Figure 5.1: Investigation to check the influence of different observing dates on the relative rotation of the two fields, as well as the overlap. The scan legs are overlaid onto a false colour Digital Sky Survey optical image, with *pink* and *green* indicating PACS and SPIRE, respectively. *Top left:* the original DSS image with sky coordinates. *Top right:* Optimal overlap on two consecutive days at an ideal moment. *Bottom left:* Observations on the same day near the end of the timing constraint, showing a borderline acceptable overlap between fields. *Bottom right:* Two cross-scans observed at either end of the constrained observation windows, demonstrating the limit in acceptable tilting between fields.

son with features at other wavelengths, but here we will only discuss the parts of this work directly related to the *Herschel* data, in particular the PACS maps.

5.2

Observations and data reduction

In this section we describe the observing strategy used to obtain the maps, and the data reduction techniques used. Furthermore, given the greater difficulty of removing instrumental artifacts in PACS data, some quality checks are performed for the latter.

5.2.1 Observations strategy

As previously mentioned, we observed a field of $\sim 5.5^\circ \times 2.5^\circ$ centred on M31, with both PACS and SPIRE in parallel mode, at a scan speed of $60''/\text{s}$. PACS data were taken at 100 and $160\ \mu\text{m}$. Images at the five wavelengths are presented in Figure 5.2. To obtain such a large map, we split our observations in two parts, A and B, each observed with a cross-scan, so that the final map is a composition of four observations. Each one covers a field of about $181' \times 150'$, centred at RA=0h37m38.870s, DEC=+40d00m51.30s (A) and RA=0h48m01.670s DEC=+42d30m33.20s (B), and they both observe an overlapping strip, parallel to the galaxy's minor axis, which is about $12'$ and $18'$ wide in PACS and SPIRE maps, respectively. These observations were scheduled on the 18th, 19th, 20th and 21st of December, 2010. Due to some issues with the star trackers, the last orthogonal scan of the northern portion of the map was lost. The field was hence observed again on the 23rd of January, 2011, so it shows a slight rotation with respect to the nominal scan.

5.2.2 PACS data reduction and quality check

The basic PACS data reduction (up to Level 1 where pixel flagging, flux density conversion, and sky coordinate association for each pixel of the detector are applied) was performed in HIPE v8, which included the most recent responsivity factors at the time. At this stage, the PACS timelines are still dominated by brightness drifts caused by low-frequency noise. In order to subtract these drifts, remove glitches, and project the timelines on the final map, we applied the IDL algorithm Scanamorphos (version 15, Roussel 2013, discussed earlier in Section 3.4.3) to the Level 1 PACS timelines. The final PACS maps have a pixel scale of $2''$ and $3''$ in the 100 (green) and $160\ \mu\text{m}$ (red) bands respectively, and the FWHM of point sources is about $12.5''$ and $13.3''$ in the green and red channel respectively (see the “PACS photometer point spread function”

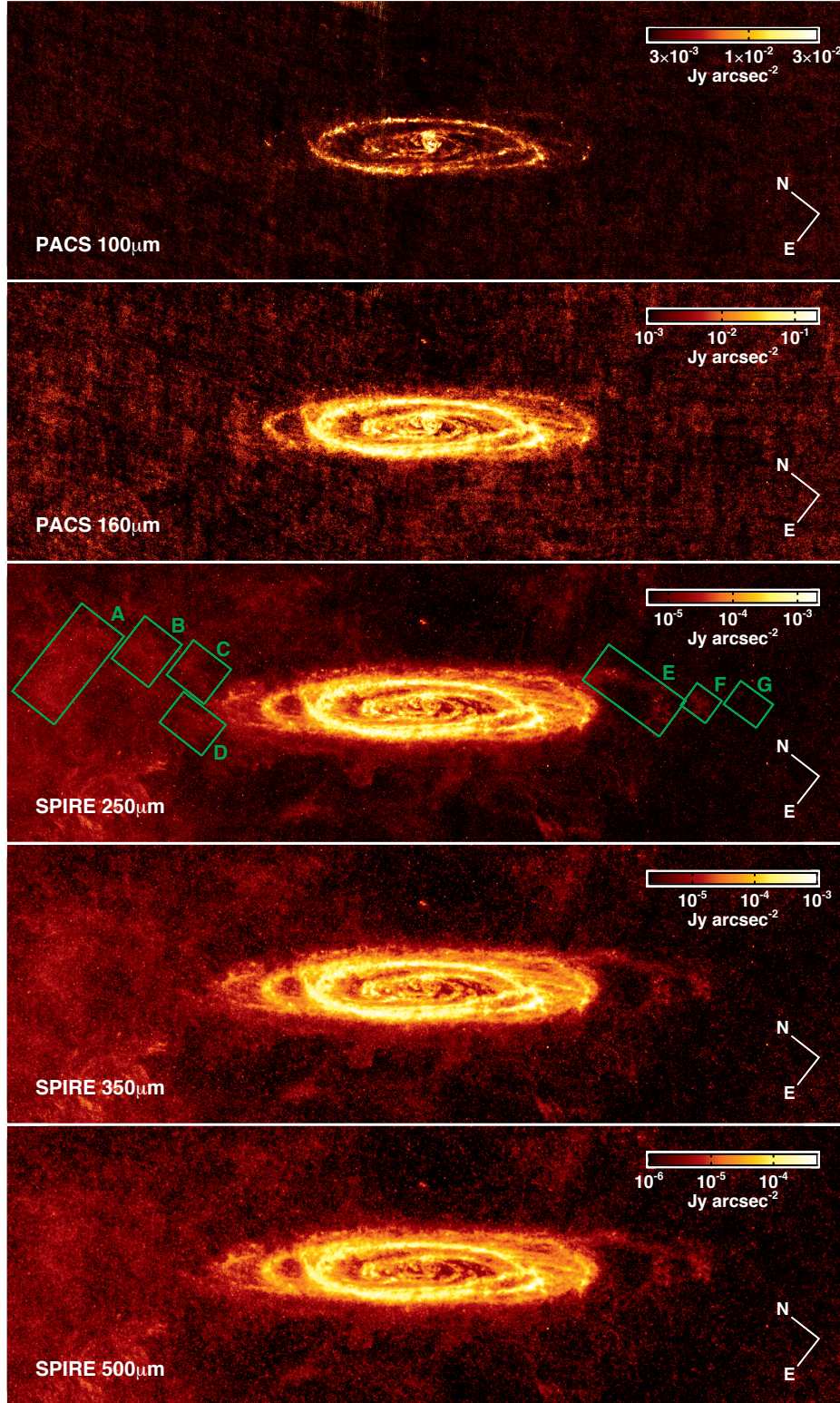


Figure 5.2: Images in the five *Herschel* bands (from top to bottom: PACS 100 and 160 μm , SPIRE 250, 350 and 500 μm). The length of the directional axes corresponds to $15'$ (~ 3.42 kpc). These are the original images, where no correction for the foreground cirrus was applied. The green rectangles in the 250 μm map represent tentative detections of dust in the outskirts (Fritz et al. 2012).

report, by D. Lutz¹). Note that, for high scan speed observations, the point spread function (PSF) is elongated in the scanning direction. This yields a spatial resolution on a physical scale of about 48.1 pc at 100 μm and 50.7 pc at 160 μm .

In order to examine the accuracy of the PACS calibration and of the flux output from Scanamorphos, we performed a pixel-to-pixel comparison between the PACS 160 μm and the *Spitzer*/MIPS 160 μm images on the one hand, and between PACS 100 μm and DIRBE (Hauser et al. 1998) at the same wavelength. We first convolved the PACS 160 μm map (respectively PACS 100 μm map) to the MIPS 160 μm (respectively DIRBE 100 μm) resolution using the convolution kernel provided by Aniano et al. (2011) (a Gaussian kernel was used to smooth the 100 μm data to the DIRBE resolution), and then resampled the maps on the same astrometric grid using the *hastrom* task in IDL. Finally, we compared the flux in each pixel of the map. PACS 100 μm and DIRBE 100 agree to within 10%, as found in (Meixner et al., in preparation). As for the 160 μm band, we confirm the non-linear behavior of MIPS above 50 MJy/sr, which was also found by Stansberry et al. (2007) and is discussed in detail by (Meixner et al., in preparation). Below this threshold, PACS and MIPS agree to within 5%, whereas the ratio PACS/MIPS is non-linear above it, leading to differences in brightness up to 30%, with MIPS underestimating the fluxes. Overall, the PACS extended calibration can be considered accurate to within 10%. A comparison of the total flux of M31 measured from PACS and MIPS maps at 160 μm , indeed yields an agreement to within about 5%. We have also investigated different baseline subtraction methods (similar to HERITAGE, see Meixner et al., in preparation) and found similar results.

Hence, in the rest of this discussion, we will adopt a 10% value as uncertainty in PACS fluxes at both wavelengths.

5.3

Dust characteristics across the galaxy

5.3.1 Dust masses and temperatures

While other works on the same data (Smith et al. 2012; Ford et al. 2013) perform a more detailed analysis and discussion of the dust properties, here we give a broad overview of the characteristics of dust in Andromeda, both as a function of the galactocentric distance and considering the whole galaxy. This approach is similar to what has already been done by other studies performed on the global, large scale IR emission (e.g. Waltherbos & Schwering 1987; Haas et al. 1998; Montalto et al. 2009). To this aim, we extract

¹ Technical Report: “PACS photometer point spread function”, Version 1.01, November 3, 2010
<http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/bolopsfv1.01.pdf>

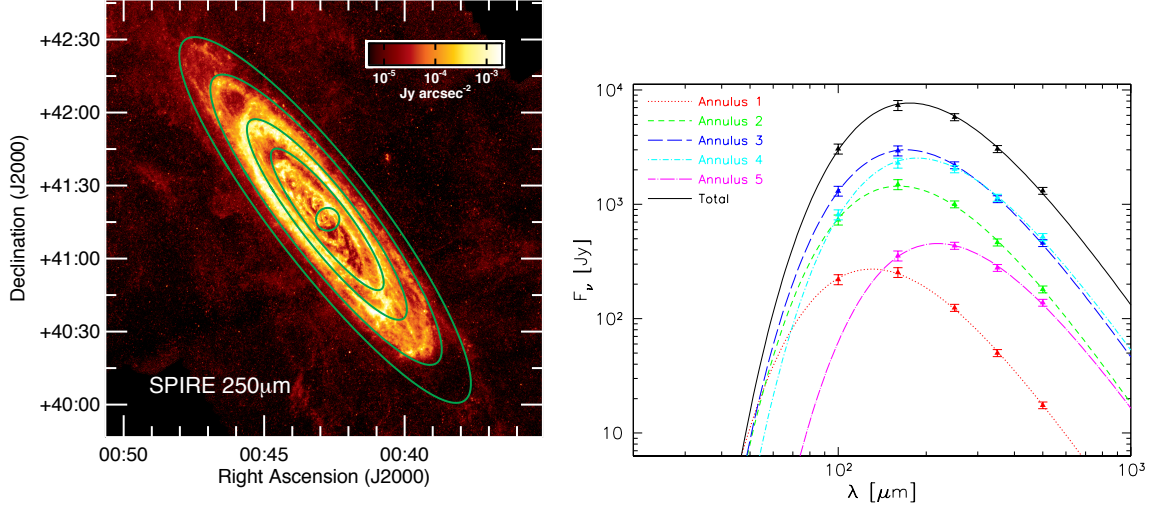


Figure 5.3: *Left:* The 250 μm SPIRE image of M31, together with the 5 apertures where fluxes were measured. The total aperture corresponds to the outermost elliptical aperture. The best fit values and uncertainties are given in Table 5.1. *Right:* The fit to the observed SEDs as measured in the four apertures: observed fluxes (triangles) are superimposed to the modified black body curve (lines), corresponding to the best fit values of the temperature. Different colours and lines correspond to different apertures/annuli (Fritz et al. 2012).

fluxes in five annuli (see left-hand panel of Figure 5.3), for which we report the sizes and characteristics in Table 5.1: the first is a circular one, and it includes the innermost dust ring ($R \sim 1.5$ kpc). The sizes of the other four were obtained by projecting circular apertures that define the inner and outer boundaries of the 10 and 15 kpc rings, plus an outermost aperture including most of the structures visible in the SPIRE 250 μm map. Their positions were chosen so that their centres coincide with the physical centres of the structures they are meant to identify (see Block et al. 2006). As a value for the position angle, we took that of M31 (38°). As *Herschel* maps differ both in resolution and pixel size, the PSFs in all maps should have in principle been matched to the broadest PSF in any map (i.e. the 500 μm PSF). We found this to be not necessary as the apertures we have used are much larger than any of the pixel and beam sizes.

We then performed a simple SED fitting, assuming that the dust thermal emission is well represented by a modified black body at a single temperature, with the emissivity described as $k_\nu = k_0 \nu^\beta$, with k_0 such that $k = 0.192 \text{ m}^2 \text{ kg}^{-1}$ at 350 μm (Draine 2003a).

We could have also used the MIPS flux at 70 μm from Gordon et al. (2006), but, as found in other works, this band is likely to be more sensitive to warmer dust, and would have required an additional modified black body component at higher temperature. Hence, the 70 μm flux was only used as an upper limit. We let the temperature be a free parameter in our fitting procedure, while the value of β was kept fixed, and initially

assumed to be 2, which is consistent with the value commonly used in dust models (Draine & Lee 1984; Li & Draine 2001). The dust mass is computed by normalising the model SED to *Herschel*'s observed data points. Uncertainties on the fluxes were conservatively assumed to be 10% for PACS (see Section 5.2.2) and 7% for SPIRE.

In the data fitting, the results of which are reported in Table 5.1 as well, we have found the best-fitting temperature by exploiting a gradient search method. Uncertainties have been computed by bootstrapping over 200 SED fits, as follows: once the best fit solution is found, a set of new, fictitious, data points is created by randomly choosing a value within the observed error bars. A best fit model is found for these new flux values, and the procedure is repeated 200 times. From the best fit models, 16% of the lower and higher values are discarded, and uncertainties are then taken as the differences between the best fit solution and the extreme values.

We compare the value of the dust mass we have obtained to the one derived by Haas et al. (1998), who use a similar approach as ours in their analysis of *ISO* data. If we consider the dust included within the fourth annulus, which is the one that better matches their global aperture, we obtain a total mass of $\sim 5.3 \times 10^7 M_{\odot}$ which is almost a factor of two higher than their $3 \times 10^7 M_{\odot}$ value, and also higher than the value derived by Gordon et al. (2006) ($4 \times 10^7 M_{\odot}$, at a temperature of 17 K). The temperature they obtain from the global SED — 16 K — agrees fairly well with the value of 16.8 K that we derive fitting the total flux within the fourth annulus, and is somewhat lower than the 18.7 K value found by Tabatabaei & Berkhuijsen (2010). The difference in the dust mass value might be, at least partially, due to the use of different dust emissivity coefficients (Haas et al. 1998 use the Hildebrand 1983 prescription for calculating the dust mass). Furthermore, the size scales used in determining the total dust mass also affect the uncertainty in the total dust mass, which has been shown by Galliano et al. (2011) to be up to $\sim 50\%$, for example, in the Large Magellanic Cloud. The value of this uncertainty will depend on the morphology of the galaxy and the mixing of the different dust phases in the area used for total dust mass determination.

We have also explored different values of β , namely 2.5, 1.7 and 1.5. The original $\beta = 2$ turned out to be the best suited value for reproducing the annuli SEDs. Only if we consider the total aperture, fits with an acceptable χ^2 were also obtained for $\beta = 1.7$, yielding in this case a temperature of 17.7 K and a total dust mass of $4.7 \times 10^7 M_{\odot}$.

The variation of the average temperature — as a function of the radius — derived with this analysis is similar, within the errorbars, to that found by Tabatabaei & Berkhuijsen (2010), derived from MIPS 70 and 160 μm images, with the exception of the central regions in which the temperature we found is lower, most likely due to both our coarser sampling, and to the fact that we are not fitting the MIPS 70 μm point, which would be

Table 5.1: *Herschel* fluxes, as measured within the five annuli we have considered (see Figure 5.3, left-hand panel). Dust temperature (T_d) and masses (M_d), and their uncertainties, are derived from SED fitting (see text for details and Figure 5.3, right-hand panel, for the SED curves fitted to the data points). We also report the mass of hydrogen in the atomic phase, as derived from HI maps of Braun et al. (2009) (both corrected and non-corrected for self-opacity), and the mass of gas in the molecular phase derived by CO data (Nieten et al. 2006). Last two columns give the total gas-to-dust ratios within the given annulus. Results for the largest annulus and for the whole galaxy are limited by the size of the CO map (see text for more details): the value indicated with ^a assumes a mass of 5% of the total, within that annulus, and the value of the gas-to-dust in the outermost annulus (^b) was computed assuming a negligible contribution from the molecular fraction, and it is hence to be interpreted as a lower limit. Values in the columns labeled with * are calculated using the self-opacity corrected maps. “A” and “B” are the major and minor axis length, respectively, of the ellipses (the first aperture is circular), given in kpc (Fritz et al. 2012).

Ap	100	160	250	350	500	A	B	T_d	M_d	M_{HI}	M_{HI}^*	M_{H_2}	G2D	G2D*
	Jy	Jy	Jy	Jy	Jy	kpc	kpc	K	$\log(M_\odot)$	$\log(M_\odot)$	$\log(M_\odot)$	$\log(M_\odot)$		
1	220	254	124	50	18	2.2	2.2	$22.2^{+0.4}_{-0.5}$	$5.66^{+0.03}_{-0.03}$	7.19	7.21	6.82	66	68
2	732	1493	1001	464	181	16.4	3.6	$18.0^{+0.3}_{-0.3}$	$6.85^{+0.03}_{-0.03}$	8.48	8.54	7.93	75	83
3	1307	2943	2200	1110	459	23.2	5.2	$17.0^{+0.3}_{-0.3}$	$7.29^{+0.03}_{-0.03}$	9.03	9.13	8.40	92	111
4	813	2302	2031	1143	518	33.6	7.5	$15.6^{+0.2}_{-0.3}$	$7.41^{+0.04}_{-0.03}$	9.31	9.42	—	^a 109	^a 140
5	—	354	435	278	138	42.4	9.5	$13.3^{+0.4}_{-0.3}$	$7.01^{+0.05}_{-0.04}$	8.99	9.08	—	^b 131	^b 158
TOT	3055	7348	5791	3047	1313	42.4	9.5	$16.5^{+0.2}_{-0.3}$	$7.76^{+0.04}_{-0.03}$	9.65	9.74	8.42	111	137

more sensitive to warmer dust.

As already found in previous studies (e.g. Haas et al. 1998; Gordon et al. 2006), the dust emission in the 1.5 kpc ring region is dominated by a higher temperature component. This is also consistent with the study by Devereux et al. (1994), who find that the gas in the innermost regions is dominated by an ionised component (seen in $H\alpha$ emission). On the other hand, if we only consider the emission from the 10 kpc ring (sampled by our third annulus), we obtain an average temperature of $17.0^{+0.3}_{-0.3}$ K, and a dust mass of $1.95 \times 10^7 M_{\odot}$. Our global SED fitting shows no need for an extra, very cold, dust component that, revealing its presence only at SPIRE wavelengths, would have been impossible to detect by former studies exploiting only data up to $\sim 170 \mu\text{m}$. This issue is tackled in more detail in (Smith et al. 2012), performing a pixel-by-pixel analysis.

5.3.2 The gas-to-dust ratio

We have calculated the mass of neutral hydrogen from the HI maps (Thilker et al. 2004; Braun et al. 2009), within the same annuli, and present it in Table 5.1. This value is multiplied by a factor of 1.36 to take the atomic He fraction into account.

The CO map, taken from Nietten et al. (2006), was used to derive the mass of molecular hydrogen (H_2) by assuming a CO-to- H_2 conversion factor $X_{CO} = N(H_2)/I_{CO} = 1.9 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Strong & Mattox 1996). This conversion factor is notoriously affected by a large intrinsic uncertainty. Values derived for M31, in particular, can range from 0.97×10^{20} to $4.6 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Leroy et al. 2011). In Smith et al. (2012) we have performed a detailed, spatially resolved analysis of dust emission considering all *Herschel* bands, and we have found values for the X_{CO} factor in the range $1.5\text{--}2.3 \times 10^{20}$, with a best-fit value of $1.9 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$.

The total molecular gas mass ($M_{\text{mol}} = M_{H_2} + M_{\text{He}}$) is then calculated by multiplying the H_2 mass value by 1.36. The CO observations only sample the region which includes the 10 kpc ring. Nietten et al. (2006) estimate that, within a region covering the innermost ~ 18 kpc, approximatively corresponding to our fourth annulus, a further 5% of CO mass is expected. In calculating the gas-to-dust ratio in the two outermost apertures (and of course in the total one), we have applied this correction, also assuming that no further molecular gas is expected at larger galactocentric distances. Hence, the values of the gas-to-dust ratio for the apertures 4, 5 and the total, that we give in Table 5.1, and that already include this correction, should be considered as lower limits, although not too distant from the actual values. In fact, it should be noted that the gas mass is dominated by the atomic phase, the molecular only contributing to the total by less than $\sim 10\%$.

That the gas-to-dust ratio in M31 is not constant throughout the galaxy, and increases as a function of the radial coordinate, was already shown by several previous studies (see e.g. Bajaja & Gergely 1977; Walterbos & Kennicutt 1988; Nedialkov et al. 2000). We estimated an average value of ~ 110 , calculated over the largest aperture (G2D column of Table 5.1), and a variation by a factor of ~ 2 from the innermost ring to the outermost annulus.

We found a very good correlation between the gas-to-dust ratio and the (average) galactocentric distance, with the first quantity exponentially increasing from the centre to the outskirts. Even though our analysis is performed over very broad apertures, we found a gradient of 0.0163 dex/kpc, which is consistent with the values of the metallicity gradient found by Trundle et al. (2002) in M31, ranging from -0.027 to -0.013 dex/kpc, under the assumption that the amount of metals locked up into dust grains is a constant fraction of the mass of interstellar metals (Edmunds 2001). Should this be the case, then the metallicity gradient would be the opposite as the one for the gas-to-dust ratio.

Braun et al. (2009) also provide HI maps where hydrogen self-opacity is taken into account. It is quite clear that the simple 21 cm integral is a lower limit to the HI mass, and M31 is one of the few cases where we have the data to account for this problem (Braun 2012). In fact, had we taken this into account, the atomic mass would have increased by a factor ranging from $\sim 5\%$ in the innermost regions, to $\sim 27\%$ in the most distant annulus. In Table 5.1 we report the HI mass and the gas-to-dust ratio calculated from the self-opacity corrected maps (columns indicated with an asterisk, *).

5.4

Concluding remarks on HELGA

We have presented and described *Herschel* PACS (100 and 160 μm) and SPIRE (250, 350 and 500 μm) observations of a $\sim 5.5^\circ \times 2.5^\circ$ field centered on the local galaxy M31. We have performed a broad analysis of the characteristics of the dust as a function of the radius. We have considered 5 main regions, described by projected circular apertures (plus an elliptical one), sampling the most significant morphological structures: the inner 1.5 kpc ring, the intra-arm region enclosed within the 10 kpc ring, the 10 kpc ring itself, the outer (~ 15 kpc) ring, and a fifth one, containing the outermost regions. A simple one-temperature modified black-body model is able to successfully reproduce the observed PACS/SPIRE SED. Average quantities, such as the dust temperature, and the gas-to-dust ratio, are derived, and they are found to strongly depend on the radius. The gas-to-dust ratio, in particular, is changing by a factor of ~ 2 , following an exponential increase across the galaxy, from the inner regions to the outskirts, as expected

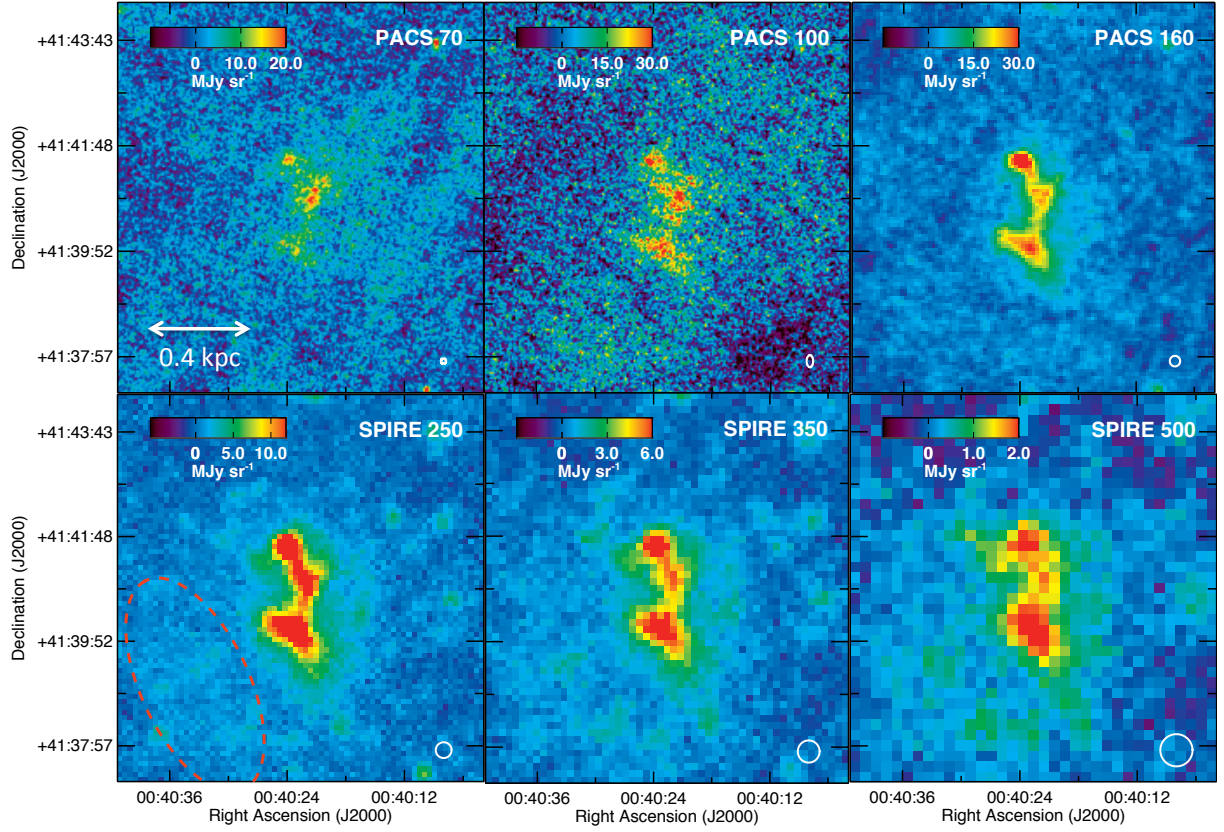


Figure 5.4: The *Herschel* images of M110 or NGC 205, all measuring $8.0' \times 6.5'$ and with standard orientation: north is up, east is left. The white circles in the bottom right corner of each panel give the FWHM of each PSF, while the red dashed ellipse indicates a possible detection below 3σ of dust coinciding with a tidal tail in the optical (De Looze et al. 2012c).

from the presence of a metallicity gradient with the opposite sign.

According to our simple emission model, the two main rings, at 10 and 15 kpc from the centre, contain the bulk (about 78%) of the dust in the galaxy. The dust surface density is highest within the 10 kpc ring, at $0.41 M_{\odot}/\text{pc}^2$, higher by a factor of ~ 4 with respect to the average value, and also higher than in the 15 kpc ring, where it is about $0.25 M_{\odot}/\text{pc}^2$.

The dust temperature is highest in the innermost aperture, but the value we derive from our SED fitting, 22 K, is considerably lower than found in previous studies (e.g. Haas et al. 1998 and Tabatabaei & Berkhuijsen 2010 derive temperatures of ~ 28 and ~ 30 K, respectively, for the nuclear dust). This is most likely due to the fact that, ignoring data shortwards of $100 \mu\text{m}$, we are not sensitive to the presence of a warmer component (e.g. Bendo et al. 2010a): this would, anyway, constitute a minor fraction of the total dust content.

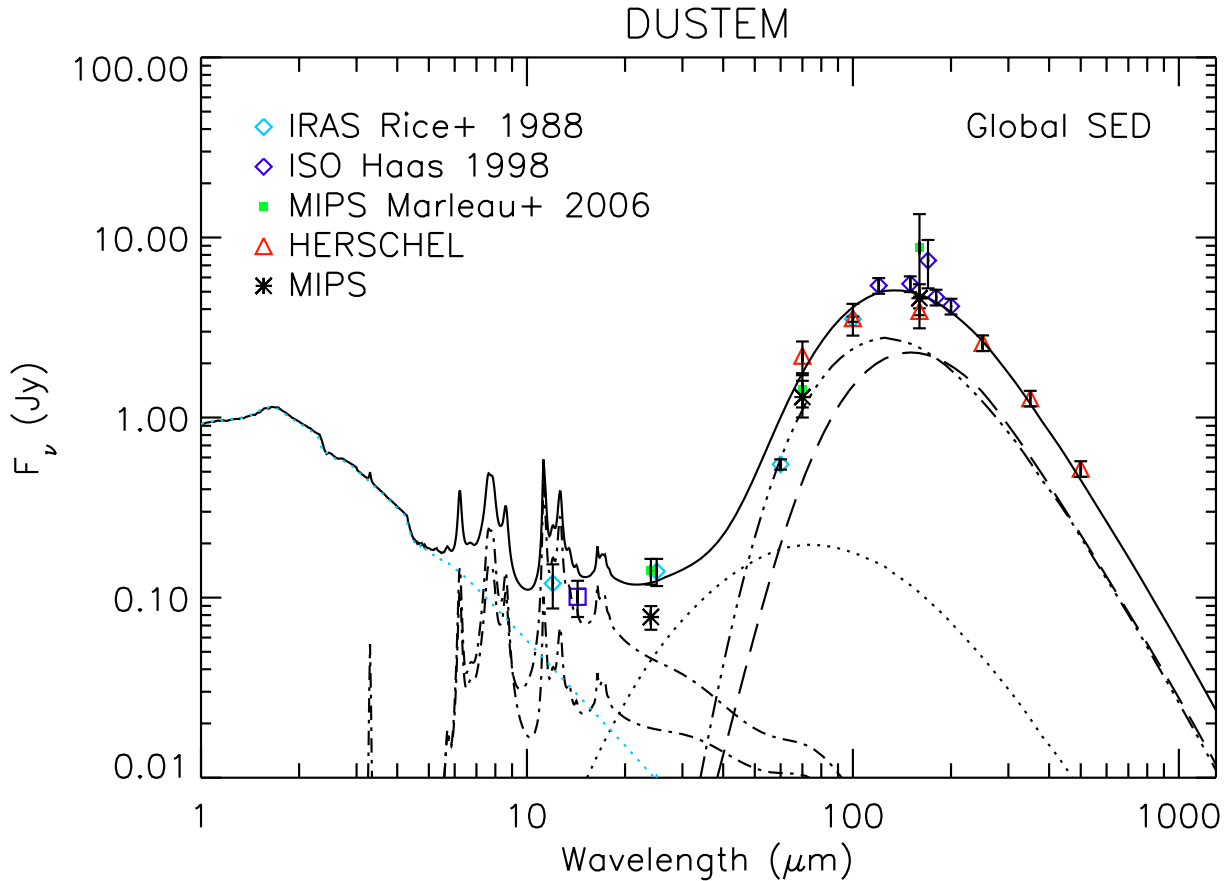


Figure 5.5: The best-fitting DustEM model SED for a silicate/amorphous carbon dust composition (solid black line) with *Spitzer*/MIPS 24 μm and *Herschel* fluxes indicated, along with literature values (Rice et al. 1988; Haas 1998; Marleau et al. 2006). The PAHs (dot-dashed line), small (dotted) and large amorphous carbon (grey) and silicate (dashed) dust grains are indicated, as well as a single stellar population component (blue dotted line) parametrised according to Maraston (1998, 2005), with a 13 Gyr age, $Z = 0.002$ metallicity and a $R_e = 130''$ effective radius, $n = 1$ index Sérsic profile (Bertola et al. 1995; De Rijcke et al. 2006), to compare with NIR/MIR observations (De Looze et al. 2012c).

5.5

An investigation of the ISM in the dwarf satellite M 110

In De Looze et al. (2012c), we combined the HELGA data with observations from the Very Nearby Galaxy Survey (VNGS), along with spectroscopic [CII] and [OI] data and ancillary molecular (CO) and atomic (HI) observations, to study the ISM contents in Andromeda's satellite early-type dwarf galaxy M 110 or NGC 205 (Figure 5.4). Based on observations of its young stellar population and a reasonable assumption for the star formation efficiency (SFE) of 10%, the current leftover gas reservoir is theoretically predicted to be at least $>10^7 M_\odot$. However, the total gas mass estimates from HI, CO and dust continuum observations come up short by about an order of magnitude ($M_g \sim 1.5 \times 10^6 M_\odot$), leading to the 'missing ISM mass problem' (Welch et al. 1998).

Table 5.2: The resulting parameters (dust temperature T_d , dust mass M_d) from the best fitting DustEM model, for the two different dust compositions, based on a pixel-to-pixel and a global SED fit (De Looze et al. 2012c).

Silicate/amorph. carbon	T_d (K)	M_d ($M_\odot$)
Pixel-to-pixel	$17.8^{+0.2}_{-0.1}$	$1.8^{+0.1}_{-0.1} \times 10^4$
Global	$20.7^{+0.5}_{-0.8}$	$1.1^{+0.1}_{-0.1} \times 10^4$
Silicate/graphite	T_d (K)	M_d ($M_\odot$)
Pixel-to-pixel	$21.2^{+0.2}_{-0.3}$	$1.1^{+0.1}_{-0.1} \times 10^4$
Global	$21.8^{+0.1}_{-1.6}$	$1.0^{+0.3}_{-0.1} \times 10^4$

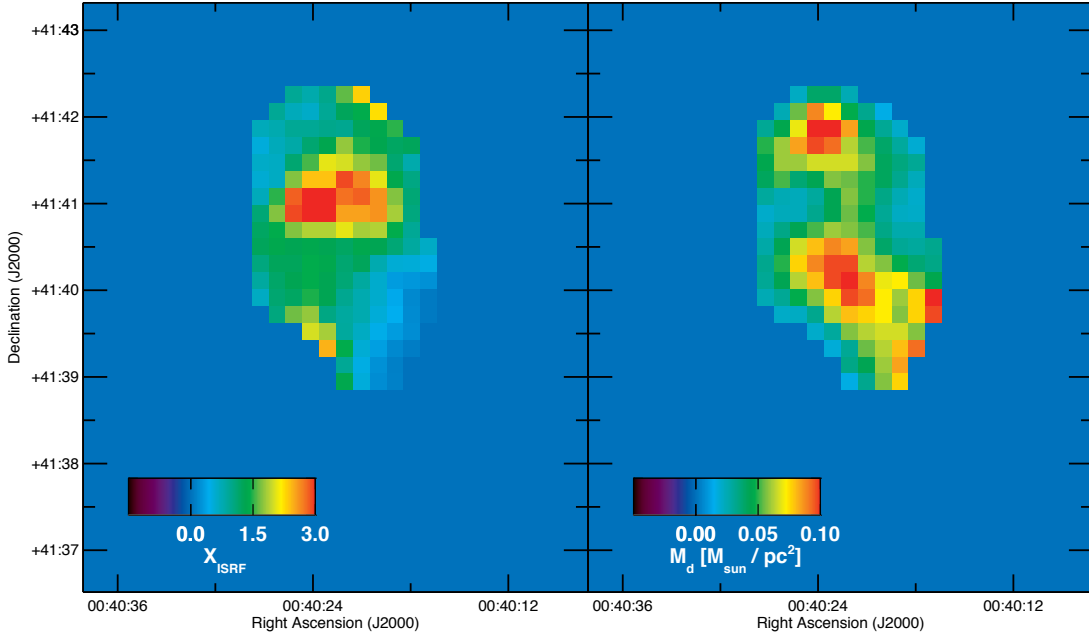


Figure 5.6: The scaling factor for a Galactic ISRF (*left*) and dust mass density (*right*) distribution resulting from the pixel-to-pixel SED fitting procedure with DustEM (De Looze et al. 2012c).

Only through the invocation of a massive cold dust component ($T_d \sim 11.6$ K) and a gas-to-dust ratio of 100 can the theoretical mass be attained (Marleau et al. 2006), but this is based on a single 1.1 mm observation of a very limited region around the core.

Using the *Herschel* capabilities, we could probe the Rayleigh-Jeans part of the SED much better to determine if such a cold dust component indeed exists. Only taking into account pixels with at least a 3σ detection in the SPIRE 250 μm map, we applied a procedure fitting the SED both on a pixel-to-pixel basis, and on a global scale. To this end, we used the DustEM code to calculate the emission by the dust (Figure 5.5), with two different compositions. Both contained PAHs and amorphous silicate grains, and this was complemented with graphite (Draine & Li 2007) and amorphous carbonaceous dust grains (Compiègne et al. 2011) respectively. The resulting dust masses

($M_d \sim 1.1\text{--}1.8 \times 10^4 M_\odot$, Table 5.2 and Figure 5.6) do not deviate much from previous values, and we put a much stricter upper limit on the mass of the cold dust component ($M_d < 4.9 \times 10^4 M_\odot$ for $T_d \sim 12$ K). The absence of any evident excess emission at $500 \mu\text{m}$ also renders it unlikely such a cold dust reservoir exists in sufficient amounts to explain the missing ISM mass.

An investigation of the [CII] and [OI] lines to probe molecular gas, which can remain partly undetected in CO observations due to the specific environment of NGC 205, also found no significant gas amounts in addition to the already known gas masses (not further discussed here; for details, see De Looze et al. 2012c). From the previously discussed dust continuum observations, we calculate a gas mass in the range $M_g \sim 4\text{--}7 \times 10^6 M_\odot$ using a gas-to-dust ratio of ~ 400 . Due to the good correlation between the gas and dust, it is unlikely the gas is selectively removed by internal or environmental mechanisms, leaving the dust behind.

From previous considerations, explanations for the missing mass in NGC 205 such as a top-heavy initial mass function (IMF), an increase of the SFE up to 65%, or feedback from an AGN have been refuted. We have found that supernova feedback and/or stellar winds expelling the gas from the inner regions, and/or tidal interactions with M 31 stripping parts of the ISM are viable explanations for the currently still prevailing missing ISM mass problem.

This Chapter (which corresponds to Verstappen et al. 2013) is structured as follows: first, we give a situational overview of the programme and its goals in Section 6.1, and in Section 6.2 we describe the sample selection and give details on the *Herschel* observations and data reduction. In Section 6.3 we derive the global fluxes for the galaxies in our sample at the PACS and SPIRE wavelengths, and we compare the values with archival fluxes at comparable wavelengths obtained with *IRAS*, *ISO*, *Akari* and *Planck*. In Section 6.4 we discuss the FIR/sub-mm morphology of the individual galaxies in detail, based on the *Herschel* maps and major axis profiles. In Section 6.5 we discuss the vertical distribution of the FIR/sub-mm emission and look for evidence of cool interstellar dust at high galactic latitudes. In Section 6.6 we apply a simple modified black-body fitting to the global fluxes to derive dust masses and temperatures, and we compare these dust masses with those obtained from radiative transfer fits to optical data. Finally, in Section 6.7 we present some conclusions about these first *HEROES* results.

6.1

Introduction to the *HEROES* programme

As discussed in Chapter 1, the most straightforward way to trace the interstellar dust in galaxies to study its amount, spatial distribution and physical properties, is by looking at FIR and sub-mm wavelengths, where the emission by cold dust grains dominates the SED. Until recently, the sensitivity, spatial resolution and wavelength coverage of the available FIR/sub-mm instrumentation has been rather limited, and most of our knowledge was often restricted to studying the global SED of galaxies (e.g. Soifer et al. 1987; Dunne et al. 2000; Pérez García & Rodríguez Espinosa 2001; Tuffs et al. 2002; Draine et al. 2007). This situation has changed substantially with the launch of the *Herschel Space Observatory* (Pilbratt et al. 2010), which has a much improved spatial resolution and wider wavelength coverage than any of its predecessors. With *Herschel*, we can now take spatially resolved FIR/sub-mm images to map the distribution of cool dust (the bulk of the dusty ISM) in nearby galaxies (e.g. Smith et al. 2010, 2012; Bendo et al. 2010a, 2012a; Pohlen et al. 2010; Kennicutt et al. 2011; Foyle et al. 2012;

Fritz et al. 2012; Boquien et al. 2012; Xilouris et al. 2012; Aniano et al. 2012; Mentuch Cooper et al. 2012; De Looze et al. 2012c).

As we also explained in Chapter 1, edge-on spiral galaxies offer an interesting perspective for studying the dust properties and distribution in spiral discs. The dust in these galaxies often shows up as prominent dust lanes in optical images, which makes this class of galaxies among the only systems where dust can easily be studied both in extinction and in emission. They are also the only systems where the vertical distribution of the dust can be studied. Due to line-of-sight projection, edge-on spirals also allow us to map the horizontal distribution of dust in detail, since the increased surface brightness enables us to trace the dust extinction and emission to large radial distances from the centre. Cold dust has been located in substantial quantities at large galactocentric radii for a small number of edge-on spirals using FIR and sub-mm observations before (e.g. Alton et al. 1998a; Dupac et al. 2003; Popescu & Tuffs 2003), but the limited sensitivity of the FIR instruments of the previous generation was a strong constraint on attempts to study the horizontal dust distribution for a larger sample of edge-on spiral galaxies.

The strongest constraints on the distribution and properties of dust in spiral galaxies can be achieved by studying the dust energy balance through a self-consistent treatment of extinction and thermal emission. Due to their special orientation with respect to us, edge-on spiral galaxies are the ideal targets for such energy balance studies. Several edge-on spiral galaxies have undergone dust distribution modelling by fitting realistic radiative transfer models to optical images (Kylafis & Bahcall 1987; Xilouris et al. 1997, 1998, 1999; Alton et al. 2004; Bianchi 2007; Baes et al. 2010b; De Looze et al. 2012a). These studies suggest that, at least for massive galaxies, the dust is distributed in a disc that is vertically thinner but horizontally more extended (by some 50% on average) compared to the stellar disc. The face-on optical depths found are typically smaller than one at optical wavelengths, indicating that the entire galaxy disc would be almost transparent when seen face-on. This result is somewhat in contradiction to the spiral disc transparency measurements using either the number of background galaxies (Holwerda et al. 2005a, 2007b) or overlapping galaxy pairs (Domingue et al. 2000; Keel & White 2001a,b; Holwerda et al. 2009, 2013). These studies find that spiral arms are opaque and discs gradually become optically thick towards the galaxy's centre.

The earlier results (Domingue et al. 2000; Holwerda et al. 2005b, 2007a) however sampled the disc in a large physical aperture (> 1 kpc) which introduces a bias against transparent regions, as they were often placed by eye or include a spiral arm. Subsequent studies used the high resolution of HST to map the transparency of a large section of the disc. When the spatial resolution is sampling below the size of a typi-

cal molecular cloud, the distribution of the disc transparency becomes an exponential one with a 0.3–0.5 drop-off depending on the Hubble Type and mass of the galaxy (Holwerda et al. 2009). With the inclusion of a size distribution of ISM clouds in SED models and more measurements of the distribution of disc transparency using occulting galaxy pairs, the two approaches are set to converge on a physical model of light transport in spiral discs.

A quantitative comparison of these spiral galaxy radiative transfer models based on optical extinction with FIR/sub-mm emission observations leads to an interesting discrepancy: the rather optically thin dust discs determined from the optical modelling absorb about 10% of the stellar radiation, whereas the FIR/sub-mm observations of normal spiral galaxies indicate they typically reprocess about 30% of the UV and optical radiation (Popescu & Tuffs 2002; Davies et al. 2012). This dust energy balance problem is particularly evident when studying individual edge-on spiral galaxies: self-consistent radiative transfer models which successfully explain the optical extinction, predict FIR/sub-mm fluxes that underestimate the observed values by a factor of about three (Popescu et al. 2000a; Misiriotis et al. 2001; Alton et al. 2004; Dasyra et al. 2005; Baes et al. 2010b; De Looze et al. 2012a). To solve this energy budget problem, two widely different scenarios have been suggested. One straightforward solution proposed is that the FIR/sub-mm dust emissivity has been underestimated significantly (Alton et al. 2004; Dasyra et al. 2005). The other scenario seeks the solution in the geometrical distribution of stars and dust, which is impossible to disentangle precisely in edge-on galaxies. If a sizeable fraction of the FIR/sub-mm emission arises from dust having a negligible influence on the extinction of the bulk of the starlight, e.g. because it is locked up in compact clumps, it can produce relatively more FIR/sub-mm emission compared to a galaxy with stars and dust smoothly mixed (Popescu et al. 2000a; Misiriotis et al. 2001; Bianchi 2008).

As indicated earlier, *Herschel* offers the possibility to study the dust emission from spiral galaxies in more detail than ever before. The combination of the sensitivity and the wavelength coverage of the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE, Griffin et al. 2010) instruments, which together cover the 70 to 500 μm wavelength region where the emission from cold dust dominates, enables us to make reliable estimates of the total thermal emission of the interstellar dust. The increase in spatial resolution compared to previous FIR instrumentation is a huge advantage: while energy balance studies in the past almost exclusively relied on integrated spectral energy distributions, *Herschel* observations allow us to trace both the vertical and horizontal distribution of FIR/sub-mm emission in detail and make the comparison with spatially resolved radiative transfer model predictions. Studies exploiting PACS and SPIRE observations

of edge-on galaxies have already demonstrated that a further leap forward in the comprehension of dust distribution and characteristics is now possible (Baes et al. 2010b; Bianchi & Xilouris 2011; Holwerda et al. 2012b; De Looze et al. 2012a,b).

This work is the first study devoted to the *HERschel* Observations of Edge-on Spirals (*HEROES*) project. As already discussed in Chapter 1, the goal of the *HEROES* project is to make a detailed study of the amount, spatial distribution and properties of the interstellar dust in a sample of seven large, edge-on spiral galaxies, and to link this to the distribution and properties of stars, interstellar gas and dark matter. This project builds strongly on new *Herschel* observations, which are crucial for a solid determination of the distribution of cold interstellar dust. However, we have also set up a multi-wavelength observational campaign to map the different components in these systems, including optical, near-infrared, HI and CO observations. Moreover, we will analyse and interpret the observational data using state-of-the-art radiative transfer simulations.

Here we concentrate on a presentation and a qualitative and quantitative analysis of the *Herschel* data. This work will be followed up by a number of other studies, which will focus on different aspects of this rich data set. In a first follow-up study we will exploit the high spatial resolution of the *Herschel* images in conjunction with *Spitzer* and *WISE* data to derive the dust properties as a function of position, by adopting a pixel-by-pixel SED fitting approach in a similar fashion as done by Smith et al. (2010, 2012). In another study we will combine existing and new optical and NIR images of the seven *HEROES* galaxies, to fit detailed radiative transfer models to these images. This study will take advantage of FitSKIRT (De Geyter et al. 2013), a fitting tool built around the SKIRT Monte Carlo radiative transfer code discussed in Chapter 2 (Baes et al. 2003, 2011) designed to fully automatically recover the structural properties of dust and stars with a particular focus on edge-on systems. These models will be used to self-consistently predict the spatially resolved FIR/sub-mm emission from each of the galaxies in our sample, extending previous attempts to panchromatic models over the entire UV/optical/NIR range. In a final planned research project we will combine the *Herschel* data with new and archival HI and CO data in order to study the spatially resolved gas-to-dust ratio in edge-on spiral galaxies out to large radii.

6.2

Observations and data reduction

6.2.1 Sample selection

The *HEROES* sample consists of seven galaxies, which were selected from a large sample of edge-on spiral galaxies according to the following criteria. The first criterion is

Table 6.1: Properties of the galaxies in our sample. The distances D are taken from NED, details on the specific adopted distance for each galaxy can be found in Section 6.2.1. The second to last column gives the conversion between angular and linear scales at the assumed distances. The last column gives the inclination of the galaxy, derived from radiative transfer modelling (see text for details).

Galaxy	RA (J2000)	Dec (J2000)	Type	M_V (mag)	PA (deg)	D (Mpc)	scale (pc/arcsec)	i (deg)
NGC 973	02:34:20	+32:30:20	Sbc	13.6	48.4	63.5	308	89.6
UGC 4277	08:13:57	+52:38:54	Sc	14.9	109.5	76.5	371	88.9
IC 2531	09:59:56	−29:37:04	Sc	12.9	75.7	36.8	178	89.6
NGC 4013	11:58:31	+43:56:48	Sb	12.1	244.8	18.6	90	89.7
NGC 4217	12:15:51	+47:05:30	Sb	12.0	49.3	19.6	95	88.0
NGC 5529	14:15:34	+36:13:36	Sc	12.9	294.1	49.5	240	86.9
NGC 5907	15:15:54	+56:19:44	Sc	11.1	154.7	16.3	79	87.2

an optical diameter of at least $4'$, in order to have sufficient spatial resolution in the *Herschel* images, even at $500\ \mu\text{m}$ (where the angular resolution is $36''$). The second criterion is somewhat more subjective: we require the galaxies to have a clear and regular dust lane. This requirement was driven by our ambition to construct detailed radiative transfer models of the observed galaxies, in order to compare the predicted FIR emission with the observations. This second requirement limits the sample to galaxies with an inclination that deviates at most a few degrees from exactly edge-on. Unfortunately, in the range so close to edge-on, galaxy inclinations cannot be easily determined in an objective way, for example based on axial ratios. This criterion also limits the sample to rather massive galaxies with rotational velocities $v_{\text{rot}} \gtrsim 120\ \text{km s}^{-1}$, as less massive galaxies tend not to show a dust lane even if their inclinations are almost perfectly edge-on (Dalcanton et al. 2004).¹

Based on these considerations, the starting point of our sample was the combination of the samples from Xilouris et al. (1997, 1999) and Bianchi (2007), since they were successful in fitting radiative transfer models to optical and NIR data with their respective codes. A number of the galaxies in this sample (NGC 4302, NGC 5746 and NGC 5965) showed evidence of irregular dust lanes and rendered modelling of the extinction very difficult to impossible, therefore they were omitted from the sample. The cut in optical diameter removed IC 1711 from the sample. Finally, the prototypical example of an edge-on galaxy, NGC 891, was omitted as it was slated to be observed by *Herschel* as part of the Very Nearby Galaxy Survey (VNGS) key programme.

¹ A complementary programme to *HEROES*, the New *HE*rschel Multi-wavelength Extragalactic Survey of Edge-on Spirals (NHEMESSES) is devoted to the study of the interstellar dust medium in a set of galaxies with $v_{\text{rot}} < 120\ \text{km s}^{-1}$ (Holwerda et al. 2012a,b).

The remaining seven edge-on spiral galaxies form the sample for the *HEROES* project (see Table 6.1 for the main properties). Distances were taken from NED according to the following criterion: if the galaxy has a redshift $z > 0.01$ (which is the case for NGC 973 and UGC 4277), we assume the Hubble flow contribution is dominant and adopt the redshift dependent distance based on the velocity with respect to the 3K CMB, using $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$; for all others we use the average value of the redshift independent distance measurements, which are mostly based on the Tully-Fisher relation. The position angles listed in Table 6.1 were either taken from Bianchi (2007), or determined from the PACS $100 \mu\text{m}$ images.

6.2.2 Herschel observations

All galaxies were observed with PACS and SPIRE separately, both with their nominal scan speed, i.e. $20''/\text{s}$ for PACS and $30''/\text{s}$ for SPIRE. Map sizes vary between $8' \times 8'$ and $16' \times 16'$ and have been chosen to cover enough surrounding sky area to characterise the background. For the PACS maps, four cross-scans (i.e. four nominal and four orthogonal scans) were performed, while the SPIRE maps were observed with a single cross-scan.

Full details on all *Herschel* observations carried out can be found in Table 6.2.

6.2.3 Data reduction

For the PACS data reduction, the *Herschel* Interactive Processing Environment (HIPE, Ott 2010) v8.0 with PACS Calibration version 32 was used to bring the raw data to Level-1, which means flagging of pixels, flat-field correction, conversion to Jansky and assigning sky coordinates to each detector array pixel. These intermediate timelines were then fed into Scanamorphos v15, an IDL program which is capable of removing the $1/f$ noise, drifts and glitches by using the redundancy in the observational data and in the end produces the resulting maps (Roussel 2013). The pixel sizes in the final maps are the default values used in Scanamorphos, i.e. $1.70''$ and $2.85''$ for the $100 \mu\text{m}$ and $160 \mu\text{m}$ maps respectively. These pixel sizes correspond to one quarter of the point spread function (PSF) full width at half maximum (FWHM) for the scan speed used in our observations, which has values of $6.8''$ and $11.4''$ at 100 and $160 \mu\text{m}$ respectively (PACS Observers' Manual). In producing the final maps, a customised sky grid was used to project the major axes horizontally.

To process the SPIRE data up to Level-1, which was done using HIPE v8.0, the official pipeline was modified into a custom script, applying the latest calibration products (calibration tree v8.1). Instead of applying the default temperature drift correction and

Table 6.2: Details of the *Herschel* observations. OD indicates the operational day of the *Herschel Space Observatory*, ObsId is the observation identification number. The PACS observations always consist of two concatenated observing blocks, one for the nominal and the other for the orthogonal scan directions. The indicated duration of the observations includes both on-source integration time and instrument and observation overheads.

OD	Target	Instrument	Duration (s)	Start date and time (UT)	ObsId	Field size (arcmin ²)
395	NGC 4013	SPIRE	349	2010-06-12 16:29:39	1342198241	8 × 8
467	NGC 5907	SPIRE	770	2010-08-24 00:47:30	1342203599	16 × 16
500	UGC 4277	SPIRE	349	2010-09-26 16:16:14	1342205086	8 × 8
558	NGC 4217	SPIRE	541	2010-11-22 21:56:09	1342210500	11 × 11
558	IC 2531	SPIRE	529	2010-11-23 05:49:48	1342210524	10 × 10
572	NGC 5529	SPIRE	529	2010-12-07 11:06:03	1342210882	10 × 10
715	NGC 5907	PACS	2124	2011-04-29 13:57:35	1342220804	16 × 16
715	NGC 5907	PACS	2124	2011-04-29 14:34:02	1342220805	16 × 16
723	NGC 4217	PACS	1217	2011-05-07 11:07:33	1342220109	11 × 11
723	NGC 4217	PACS	1217	2011-05-07 11:28:53	1342220110	11 × 11
723	UGC 4277	PACS	813	2011-05-07 12:43:07	1342220119	8 × 8
723	UGC 4277	PACS	813	2011-05-07 12:57:43	1342220120	8 × 8
731	NGC 4013	PACS	813	2011-05-15 12:13:15	1342220968	8 × 8
731	NGC 4013	PACS	813	2011-05-15 12:27:51	1342220969	8 × 8
733	IC 2531	PACS	909	2011-05-17 05:29:37	1342221271	10 × 10
733	IC 2531	PACS	909	2011-05-17 05:45:49	1342221272	10 × 10
758	NGC 5529	PACS	909	2011-06-11 17:40:01	1342222509	10 × 10
758	NGC 5529	PACS	909	2011-06-11 17:56:13	1342222510	10 × 10
787	NGC 973	PACS	813	2011-07-10 10:55:12	1342223868	8 × 8
787	NGC 973	PACS	813	2011-07-10 11:09:48	1342223869	8 × 8
828	NGC 973	SPIRE	349	2011-08-20 10:49:43	1342226629	8 × 8

median baseline subtraction, we used a custom method called BRIGADE (Smith et al. in prep.) to correct for the temperature drifts. The final SPIRE maps were produced with the naive mapper, using pixel sizes of 6'', 8'' and 12'' for the 250 μm , 350 μm and 500 μm maps respectively. These sizes were chosen to measure about a third of the SPIRE beams' FWHM, having values of 18.2'', 24.5'' and 36.0'' respectively (SPIRE Observers' Manual²). As was the case for the PACS maps, the final SPIRE maps were projected onto a sky grid with a horizontal major axis.

Due to some internal calibration adjustments on the satellite, observations performed during operational day (OD) between 320 and 761 might suffer from pointing accuracy

² http://herschel.esac.esa.int/Docs/SPIRE/pdf/spire_om.pdf

Table 6.3: Global PACS and SPIRE fluxes and the major and minor semi-axes of the used elliptical apertures for the galaxies in the sample. All fluxes include a colour correction.

Galaxy	F_{100} [Jy]	F_{160} [Jy]	F_{250} [Jy]	F_{350} [Jy]	F_{500} [Jy]	a [$''$]	b [$''$]
NGC 973	4.04 ± 0.20	4.92 ± 0.24	3.84 ± 0.41	1.81 ± 0.28	0.69 ± 0.17	144	71
UGC 4277	1.46 ± 0.09	2.89 ± 0.13	2.48 ± 0.34	1.38 ± 0.24	0.58 ± 0.18	139	74
IC 2531	5.22 ± 0.26	10.07 ± 0.50	6.70 ± 0.64	3.62 ± 0.40	1.57 ± 0.24	240	78
NGC 4013	22.36 ± 1.12	32.04 ± 1.60	18.27 ± 1.34	7.93 ± 0.63	2.77 ± 0.32	192	95
NGC 4217	38.69 ± 1.94	56.79 ± 2.84	28.79 ± 2.07	12.27 ± 0.94	4.25 ± 0.39	216	118
NGC 5529	7.91 ± 0.40	12.89 ± 0.65	8.42 ± 0.73	4.25 ± 0.47	1.74 ± 0.27	241	87
NGC 5907	57.35 ± 2.87	88.56 ± 4.43	54.21 ± 3.93	25.83 ± 1.98	10.11 ± 0.87	386	112

issues, and may not always be trustable. All of our observations, apart from those for NGC 973, could then be affected by potential astrometry issues. We have taken this into account in the data reduction by using the pointing product supplied by the HSC³.

6.2.4 Optical Images

V-band images used for this work are a combination of both data already available in the literature and new observations. UGC 4277, NGC 5529, NGC 4013 and NGC 4217 are from Bianchi (2008, Section 2 giving a detailed presentation of these data). Data for IC 2531 are taken from Xilouris et al. (1999, a detailed description is given in their Section 2). Finally, data for NGC 5907 and NGC 973 are from newly performed observations at the Telescopio Nazionale Galileo (TNG). Both galaxies were observed in 5 exposures of 150 seconds between August and October 2011, with a seeing of about $1.5''$. As NGC 973 is located close to a bright star, causing severe reflection effects on the first observations, it was re-observed with a rotated field of view to avoid the bright star. NGC 5907 is larger than the TNG-DOLORES field of view, so that two different observations had to be combined.

Optical images are shown here (see Figures 6.2 to 6.8) mainly for illustrative purposes, as they will be exploited in future works in the frame of the *HEROES* project.

6.3

Global fluxes

We determined the global flux of the seven *HEROES* galaxies in the two PACS and three SPIRE bands using aperture photometry. We adopted the same approach as de-

³ <http://herschel.esac.esa.int/twiki/bin/view/Public/HowToUseImprovedPointingProducts>

scribed in Dale et al. (2012) for the flux determination, background subtraction, and uncertainties calculation. To derive the total fluxes we defined, for each galaxy, an elliptical aperture, roughly centred on the galaxy itself. For each galaxy, the size of the aperture is defined in such a way that it encompasses all the emission at $500\ \mu\text{m}$, as this band has the poorest spatial resolution. No aperture corrections were applied to the measured fluxes. In any case, using the image at the poorest resolution to define the ellipses within which fluxes are calculated should ensure that no flux is lost. As a further check, we performed flux measurements on the $500\ \mu\text{m}$ images by choosing various apertures at increasingly higher a and b (major and minor axis of the ellipses, respectively) values. The results make us confident that even at the longest wavelength we are not missing any significant fraction of the extended emission.

The lengths of the major and minor semi-axes are reported in Table 6.3 for each galaxy. We then used the DS9/Funtools program FUNCTS, which sums the flux value of each pixel inside the aperture, to yield the global flux. Sky subtraction is performed as follows: we define a number of circular apertures surrounding the galaxy, far enough so that they are not contaminated by its emission, but as close as possible to the galaxy in order to better sample the sky properties of its surroundings, also making sure they do not include any background source. A mean sky level per pixel is then computed from these apertures and this value, multiplied by the number of pixels encompassing the galaxy within the elliptical aperture, is subtracted from the global flux measured as explained before.

A colour correction factor is included, taken from the ICC’s relevant document⁴ and from the SPIRE Observers’ Manual⁵, respectively. For PACS, we used the tabulated values relative to a modified black body with temperature of 20 K and emissivity index $\beta = 2$, which are both well suited for the SEDs of our objects (see Section 6.6.2; values relative to $T = 15\ \text{K}$ were adopted for UGC 4277 as its best fit model favours a lower temperature). As for SPIRE, we used colour correction values calculated for extended sources, with an index $\alpha_S = 4$ (which turned out to be the most appropriate choice of $\beta = 1.8$). A calibration correction factor was also applied to account for the fact that our sources are extended (see SPIRE Observers’ Manual, Section 5.2.8).

As for the uncertainties, we calculate the total uncertainty by summing in quadrature the calibrations uncertainty (5 and 7 % for PACS and for SPIRE, respectively⁶) and the uncertainty on the sky level, which we compute as in Equation (2) in Dale et al. (2012).

⁴ Technical Report: “PACS Photometer Passbands and Colour Correction Factors for Various Source SEDs”, Version 1.0, April 12, 2011

⁵ Version 2.4, June 7, 2011

⁶ See PACS Observers’ Manual, Version 2.3, and SPIRE Observers’ Manual, Version 2.4

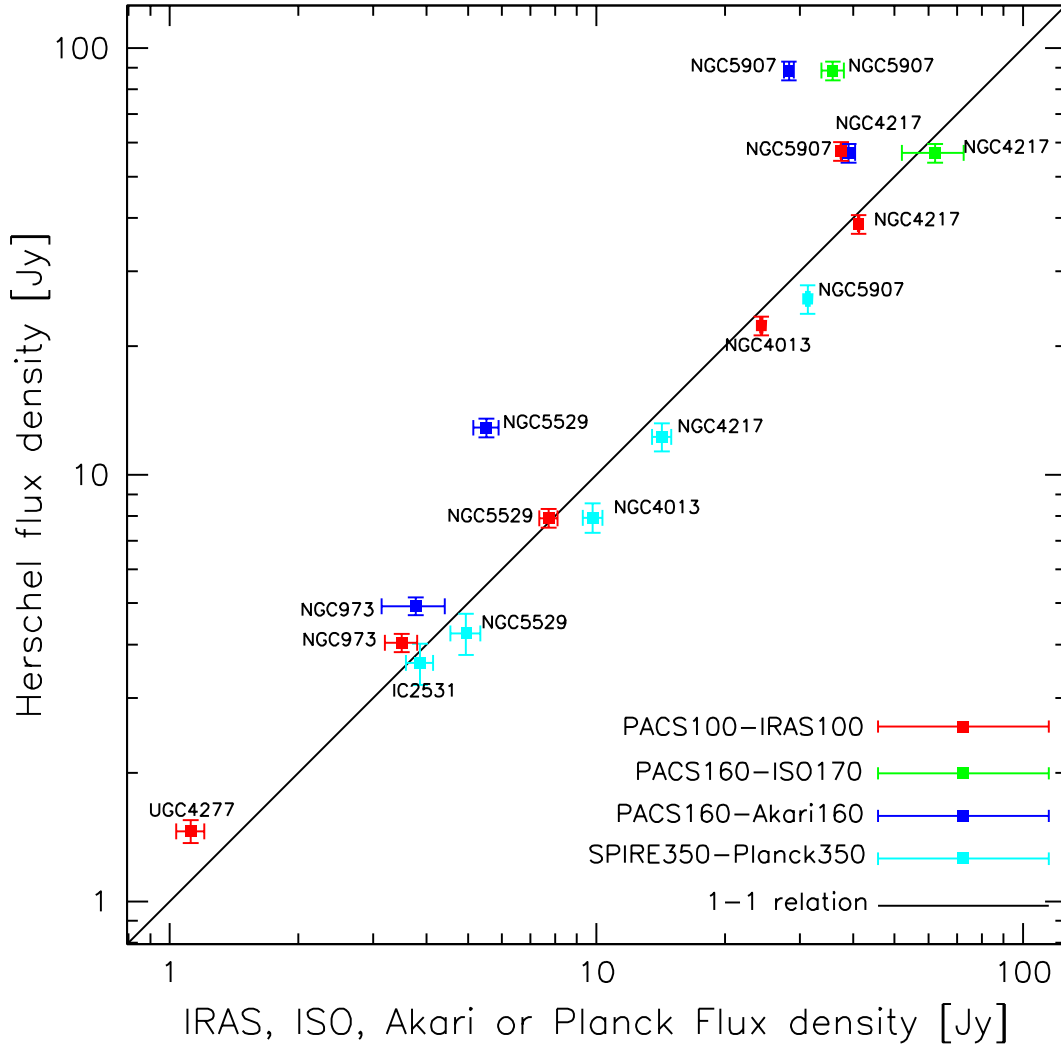


Figure 6.1: Comparison between the PACS 100 μm , PACS 160 μm and SPIRE 350 μm fluxes with IRAS, ISO, Akari and Planck fluxes.

As a check on the accuracy of the derived flux densities (fluxes are reported in Table 6.3), we searched in the literature and various archives for other flux densities at similar wavelengths. For all galaxies but IC 2531, IRAS flux densities are available at 100 μm (Moshir et al. 1990; Sanders et al. 2003; Lisenfeld et al. 2007). All galaxies except NGC 973 and UGC 4277 were detected by *Planck* in the Early Release Compact Source Catalog (Planck Collaboration et al. 2011). The two brightest galaxies in our sample, NGC 5907 and NGC 4217, were detected by *ISO* as part of the ISOPHOT 170 μm Serendipity Survey (Stickel et al. 2004). Finally, four galaxies (NGC 973, NGC 4217, NGC 5529 and NGC 5907) are listed in the *Akari*/FIS All-Sky Survey Point Source Catalogue (Yamamura et al. 2010).

Figure 6.1 shows the comparison of the PACS 100 μm , PACS 160 μm and SPIRE 350 μm

fluxes of the *HEROES* galaxies with the *IRAS* 100 μm , *Akari* 160 μm , *ISO* 170 μm and *Planck* 857 GHz fluxes respectively. The solid line in the plot shows the one-to-one relationship. The agreement between the *Herschel* fluxes and the archival *IRAS*, *ISO* and *Planck* (aperture) fluxes is generally excellent. The only exception is NGC 5907, where the PACS 100 and 160 μm fluxes deviate significantly from the *IRAS* 100 μm and ISOPHOT 170 μm fluxes respectively: 57.35 versus 37.43 Jy at 100 μm and 88.56 versus 35.83 Jy at 160/170 μm . A possible explanation is the large extent of this galaxy, which is resolved even by the 2.94' *IRAS* 100 μm beam (Soifer et al. 1989). The SPIRE 350 μm flux (25.83 ± 1.98 Jy) and *Planck* 857 GHz flux (27.25 ± 0.69 Jy) of NGC 5907 are in excellent agreement.

While the agreement between *IRAS*, *ISO* and *Planck* on the one hand, and *Herschel* on the other hand is very good, Figure 6.1 shows that the agreement between the PACS 160 μm flux densities and the *Akari*/FIS 160 μm flux densities is very poor. The PACS fluxes are on average a factor two higher than the *Akari* fluxes. This difference is probably due to the way *Akari* fluxes are measured, i.e. similarly to PSF fitting. While the PSF of *Akari* is about 60'' at 160 μm , all the galaxies in our sample are much larger, so it is indeed expected that the latter are smaller than the *Herschel* fluxes.

6.4

FIR/sub-mm morphology

In this Section we describe the far-infrared morphology of the observed galaxies, based on the PACS and SPIRE maps presented in Figures 6.2 through 6.8. We also produce horizontal profiles of the FIR/sub-mm emission in each of the *Herschel* bands, which we present in Figure 6.9. These profiles were derived by integrating the flux over the image pixels along strips parallel to the minor axis and averaging through division by the number of pixels used for each strip. The area used for this procedure was a rectangle centred on the galaxy, having sizes equal to the major and minor axes of the elliptical apertures used in the flux determination (Table 6.3). These profiles are hence a sort of average surface brightness profiles along the horizontal direction. We used these collapsed profiles instead of straight cuts along the major axis to increase the signal-to-noise.

We compare the observed profiles to the theoretical horizontal one expected from the so-called double-exponential model, described by the three-dimensional density distribution

$$\rho(R, z) = \frac{M_d}{4\pi h_R^2 h_z} \exp\left(-\frac{R}{h_R} - \frac{|z|}{h_z}\right) \quad (6.1)$$

with R and z the horizontal and vertical position within the system's coordinates, M_d

the total dust mass, and h_R and h_z the dust's horizontal scalelength and vertical scale-height, respectively. This model is the most commonly adopted description of the three-dimensional distribution of dust in spiral galaxies (e.g. Xilouris et al. 1997, 1998, 1999; Alton et al. 2004; Bianchi 2007, 2008; Popescu et al. 2011). If this system is perfectly edge-on, with the major axis aligned to the x -axis, it has a mass surface density distribution which is described by the following:

$$\Sigma(x, y) = \frac{M_d}{2\pi h_R h_z} \left(\frac{|x|}{h_R} \right) K_1 \left(\frac{|x|}{h_R} \right) \exp \left(-\frac{|y|}{h_z} \right) \quad (6.2)$$

where K_1 is the modified Bessel function of the first order (see e.g. Kregel et al. 2002, Equation 2). When we collapse this surface density distribution in the vertical direction and normalise the resulting expression, we find as horizontal profile:

$$\Sigma_{\text{hor}}(x) = \frac{1}{\pi h_R} \left(\frac{|x|}{h_R} \right) K_1 \left(\frac{|x|}{h_R} \right) \quad (6.3)$$

In Figure 6.9 we also show these exponential models with scalelengths determined from modelling of optical data taken from the literature (see Table 6.5), represented with black crosses. However, it should be pointed out that these models only describe the dust distribution, while the actual data profiles from the *Herschel* maps show instead the characteristics of the dust emission, such as its temperature. For most galaxies in our sample, the 500 μm profiles follow this exponential model to a reasonable degree, although even this model is incomplete: it fails to include the truncation of the dust disc. Vertical profiles were derived in a similar fashion; these are presented in Figure 6.10 and discussed in Section 6.5.

Information such as distances, optical radius, morphological and spectral types are taken from the NASA Extragalactic Database (NED)⁷.

6.4.1 NGC 973 [UGC 2048]

NGC 973 is located at a distance of 63.5 Mpc and has a D_{25} diameter of 4.03'. Its morphological class is estimated to be Sb or Sbc, due to the inherent uncertainty of the precise structure of edge-on galaxies, and it is classified as a Seyfert 2/LINER galaxy. The inclination is found to be $89.6^\circ \pm 0.1^\circ$ (Xilouris et al. 1997) and the galaxy is showing a prominent dust lane (Guthrie 1992) over its entire span, from the centre to the edges. Although Pildis et al. (1994) claimed not to have found any extraplanar emission-line gas in H α , Miller & Veilleux (2003) did detect some extraplanar emission from gas, but

⁷ <http://ned.ipac.caltech.edu/>

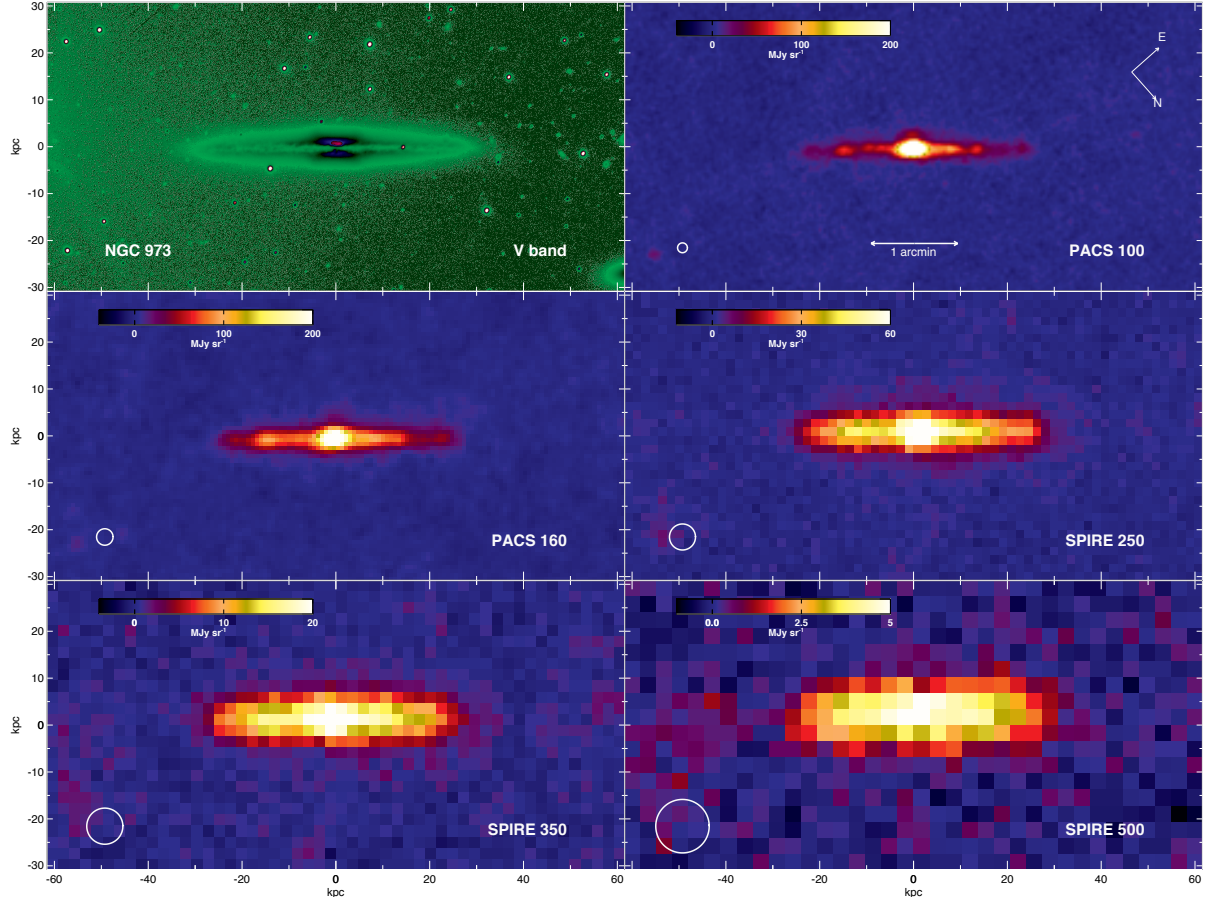


Figure 6.2: Optical V-band and *Herschel* PACS and SPIRE images for NGC 973. The image sizes are about $6' \times 3'$. The orientation and length scale are given in the top right panel. The band for each panel is shown in its bottom right corner, with the *Herschel* beam size indicated by the circle in its bottom left corner.

also mentioned there is no suggestion of a widespread diffuse emission above the disc plane. It is assumed the dust shows the same or at least similar behaviour. A previous attempt to model the dust distribution was presented in Xilouris et al. (1997), resulting in a dust scalelength of $50''$ or 16.3 kpc, about 50% longer than the equivalent stellar disc scalelength.

The different wavelength maps, horizontal and vertical profiles for NGC 973 are shown in Figures 6.2, 6.9 and 6.10 respectively. This galaxy demonstrates a very peculiar behaviour in its horizontal profiles compared to the other galaxies in the sample. For one thing, the surface brightness shows a relatively shallow decline, out to about $1.4'$ on the SW side and about $1.4'$ to $1.6'$ — depending on the wavelength — on the NE side of the disc and then falls down dramatically, suggesting a possible truncation of the dust disc. In addition to this, the emission shows a very sharp and strong central peak at PACS wavelengths, which has almost completely vanished from $350 \mu\text{m}$ onwards, partly because of the poorer spatial resolution at these latter wavebands. This

strong peak is overshadowing the other secondary peaks visible at PACS wavelengths on either side (at roughly $0.75'$ and — to a lesser extent — $1.2'$ from the centre).

The central peak clearly visible in both the 100 and 160 μm horizontal profiles might be linked to the fact that this galaxy hosts an active galactic nucleus, which would then be responsible for the compact, warmer emission in the innermost regions. We checked whether this peak is compatible with a point-like emission, as expected — at these resolutions — for an AGN-like source. To do so, we convolved a set of gaussians with the 1-dimensional PSF profile derived from PACS PSF (Aniano et al. 2011), and subtracted them from the horizontal profile derived at 100 μm , the highest resolution data. We found that the central peak is compatible with a gaussian profile emission with an upper limits on the central source's FWHM of $1.5''$, corresponding to a physical scale of ~ 450 pc. Due to the low spatial resolution at SPIRE wavelengths it is very difficult to draw any further conclusions about the disc structure.

6.4.2 UGC 4277

UGC 4277 is the most distant galaxy in our sample at a distance of 76.5 Mpc, with a D_{25} diameter of $3.9'$ and a classification as an Sc or Scd type galaxy. It has an inclination of 88.89° (Bianchi 2007), with a clear dust lane visible from the centre to the edges. Modelling of the dust distribution has been previously carried out in Bianchi (2007), giving a dust scalelength of $35''$ or 12.5 kpc, which is about the same as the fitted stellar disc scalelength.

The horizontal profiles for UGC 4277 — maps are given in Figure 6.3 — show a rather erratic behaviour. At 100 μm , a number of small peaks are visible, but none of these can be pinned down as the central one. On top of that, a smaller secondary peak about $1.3'$ off centre toward the east end of the galaxy is almost separated from the rest of the disc by a clear drop in emission at this wavelength and emission levels fall sharply just beyond this peak, while on the other side, the profile gets dominated by the background somewhere around $1.5'$ away from the centre. The other PACS wavelength is more symmetrical, with one central peak and one secondary about $0.5'$ off centre on either side — though all three have roughly the same strength — and the profile drops off very steeply beyond these secondaries, but first levels out at a reduced plateau before falling off farther beyond $1.3'$ on both sides. At SPIRE wavelengths, the surface brightness seems to be smoother, maintaining a plateau up to $0.4'$ to $0.5'$ from the centre before declining down to the background at about $1.6'$ off centre.

An exponential distribution for the dust turns out to be a fairly good representation of the observed horizontal profiles at SPIRE wavelengths while PACS profiles are characterised by a more irregular behaviour. The only clearly distinguishable feature in the

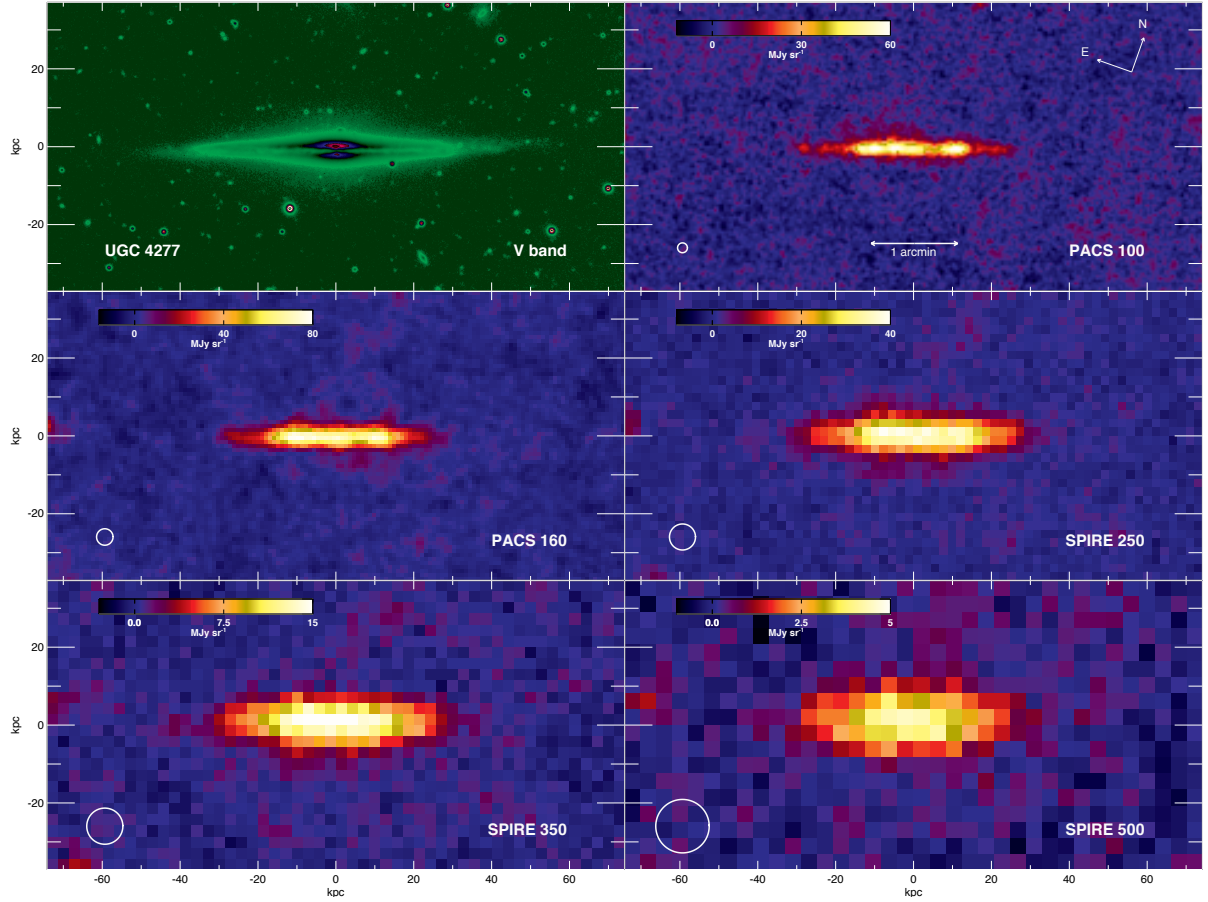


Figure 6.3: Optical V-band and *Herschel* PACS and SPIRE images for UGC 4277. The image sizes are about $6' \times 3'$.

maps is a concentration of the surface brightness on one side of the centre at $100 \mu\text{m}$, rendering the structure of the dust disc hard to determine.

6.4.3 IC 2531

IC 2531 is the only galaxy on the southern hemisphere in our sample. It is located at a distance of 36.8 Mpc and it has a D_{25} diameter of $7.5'$. It is classified either as an Sb or as an Sc type galaxy showing HII regions, and it is characterised by a conspicuous peanut-shaped or boxy bulge (Jarvis 1986; de Souza & Dos Anjos 1987). With a fitted inclination of $89.6^\circ \pm 0.2^\circ$ (Xilouris et al. 1999), this galaxy is oriented almost perfectly edge-on. The dust lane is very prominent and regular, and extends from the galactic centre to the edge of the disc, as well as into the higher stellar layers, which is evidenced by dust features traceable up to a few scaleheights (de Grijs & Peletier 2000). Many attempts have been made to determine the dust distribution from fitting extinction models to the dust lane by several works including Wainscoat et al. (1989), Just et al. (1996), Kuchinski et al. (1998) and Xilouris et al. (1999), but only the latter

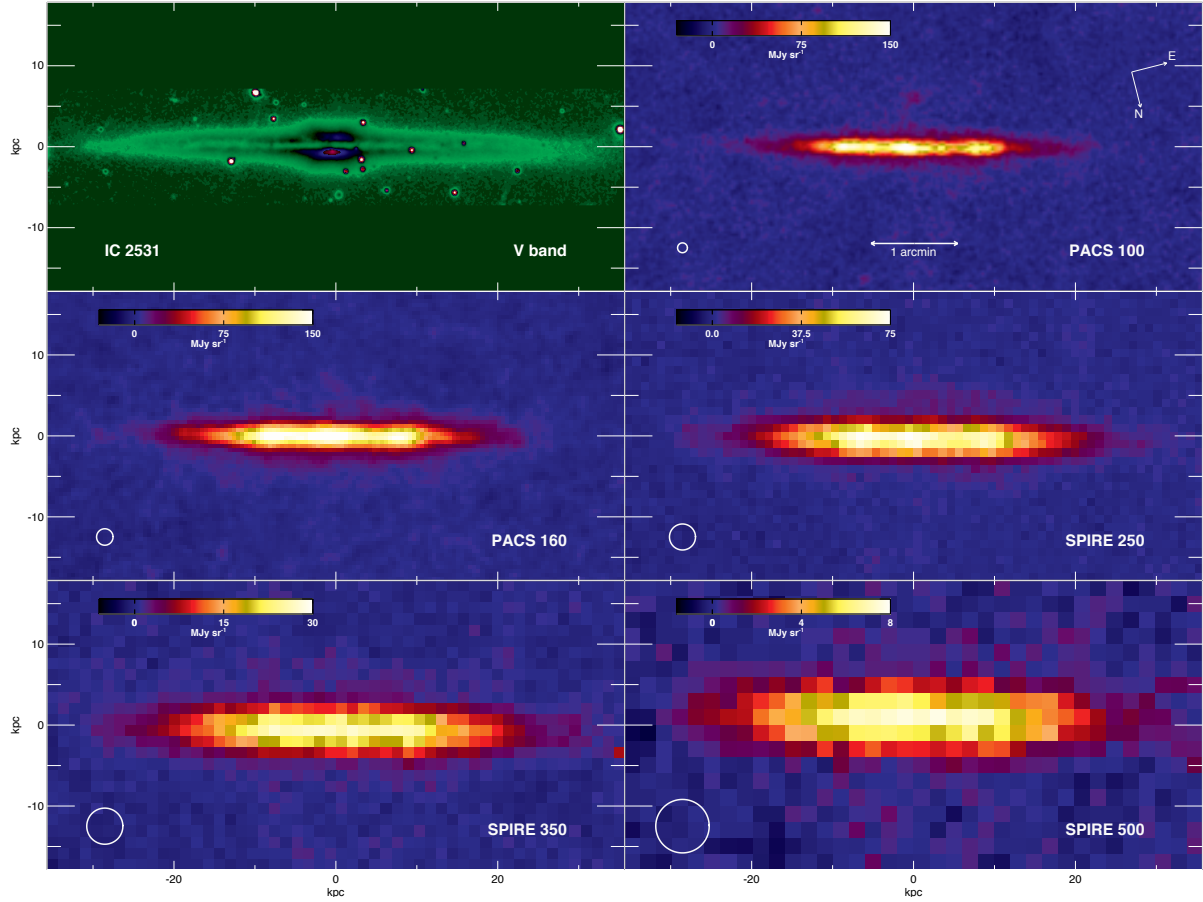


Figure 6.4: Optical V-band and *Herschel* PACS and SPIRE images for IC 2531. The image sizes are about $6' \times 3'$.

performed a global fit. According to the model by Xilouris et al. (1999), which includes both absorption and scattering, the dust in IC 2531 has a horizontally extended distribution with a scalelength of $75''$ or 13.7 kpc, about 50% larger than the fitted stellar scalelength.

The maps for IC 2531 are shown in Figure 6.4. Apart from the one at $500 \mu\text{m}$, all horizontal profiles show a plateau with a primary central peak and clear secondary peaks symmetrically positioned around the centre at a distance of roughly $1'$, beyond which point they drop off sharply, out to about $2'$ to $2.5'$ from the centre, where they are no longer distinguishable from the background. Possibly due to the lower resolution, the surface brightness at $500 \mu\text{m}$ remains almost flat from the centre out to about $1.5'$ on either side, where it starts to drop off, though not as sharp as in the other bands.

Because of the clear secondary peaks, especially the $100 \mu\text{m}$ map indicates a possible ring-like or spiral structure, along with a more diffuse dust disc, although this could simply be the continuation of the same structure seen edge-on. It is also not clear whether this is a single structure or possibly two or more concentric rings — as indi-

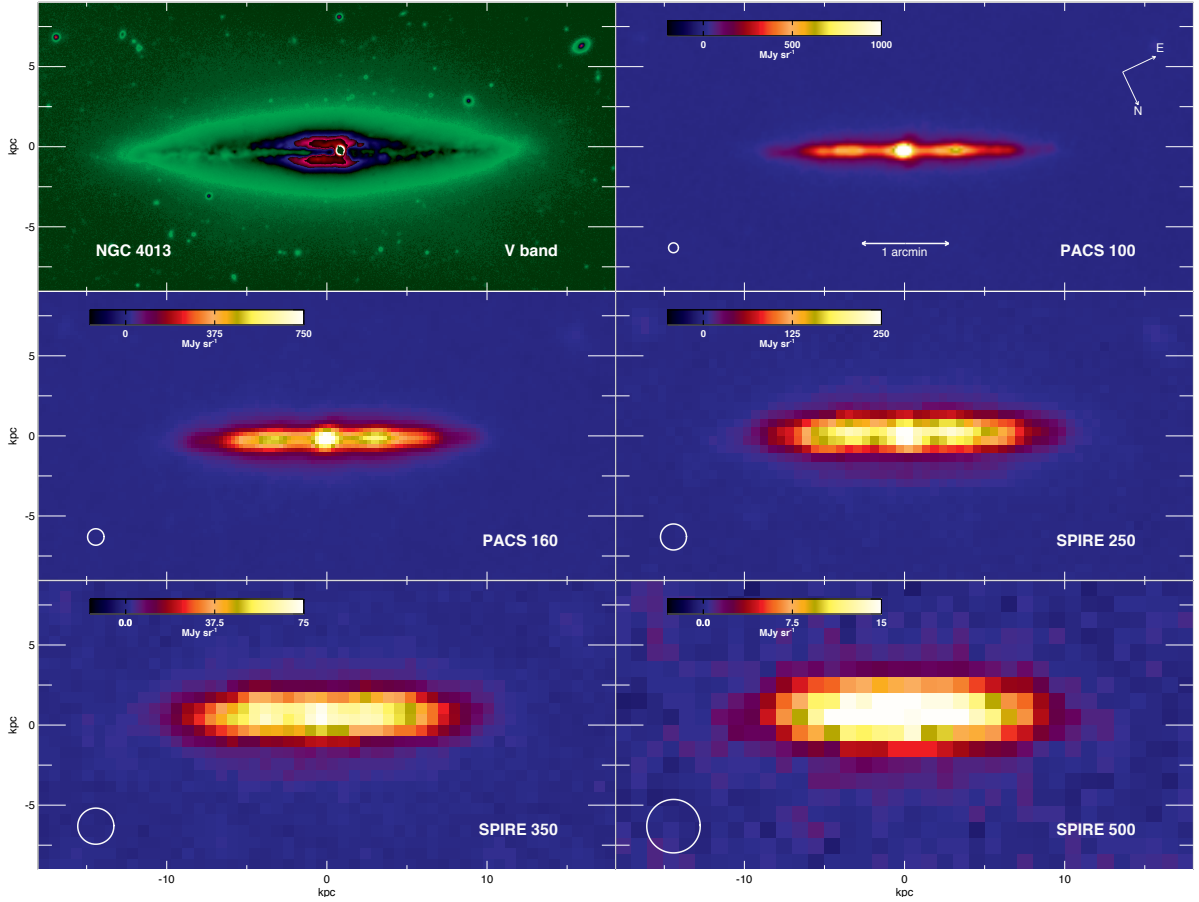


Figure 6.5: Optical V-band and *Herschel* PACS and SPIRE images for NGC 4013. The image sizes are about $6' \times 3'$.

cated by the slight revival of the $100 \mu\text{m}$ emission at about $1.5'$ on either side of the centre.

6.4.4 NGC 4013

At a distance of 18.6 Mpc, NGC 4013 has a D_{25} diameter of $5.2'$, is variously classified as an Sbc (Xilouris et al. 1999), an Sb or an SAb type galaxy with HII regions and is considered a LINER galaxy. Furthermore, the galaxy possesses a box-shaped bulge (Jarvis 1986; de Souza & Dos Anjos 1987) and shows a very clear warp in various bands but sometimes in opposite directions for the dust, gas and stellar component of the galaxy disc (Bottema et al. 1987; Sanchez-Saavedra et al. 1990; Florido et al. 1991; Bottema 1995, 1996), although Xilouris et al. (1999) claim the stellar distribution in their optical images has no warp significant enough to affect their model. The inclination angle estimates for this galaxy vary from $89.7^\circ \pm 0.1^\circ$ (Xilouris et al. 1999) to 89.89° (Bianchi 2007). Apart from a bright foreground star blocking the view, the dust lane in this galaxy can be clearly traced from the centre out to the furthest edges as well as out

of the central plane in optical images from Howk & Savage (1999), especially at larger radii where the bulge no longer dominates. Its dust distribution has been previously modelled with global fits to optical extinction data in Xilouris et al. (1999) and Bianchi (2007), resulting in dust scalelengths varying from $45''$ or 3.9 kpc (Xilouris et al. 1999) to $30''$ or 2.7 kpc (Bianchi 2007), corresponding to about 25% longer (Xilouris et al. 1999), respectively shorter (Bianchi 2007), than the stellar disc scalelength. Furthermore, Comerón et al. (2011) have found evidence of a substantial secondary thick disc and a third stellar vertically extended disc structure.

The different wavelength maps for NGC 4013 are presented in Figure 6.5. The horizontal profiles show a very sharp central peak at $100\ \mu\text{m}$, as well as symmetrically located secondary peaks about $0.6'$ off centre, although the latter have a difference in strength, with the one at the NE end of the disc being slightly brighter. Both primary and secondary peaks stand out above a plateau level, which reaches out to about $0.6'$ to $1'$ either side of the centre, while the peaks seem to have evened out at $350\ \mu\text{m}$ and beyond, most probably due to the coarser resolution. Beyond the plateau, the profiles become much steeper, up to about $1.3'$ to $2'$ from the centre, where the background begins to dominate.

The horizontal profile displays a substantial departure from the simple exponential model we superimposed to the data, at PACS wavelengths, due to the highly peaked emission, while it is more consistent at the longest wavelengths. The PACS maps are, in fact, largely dominated by the emission coming from the central region, possibly contaminated by some nuclear activity as its LINER classification hints at. Similarly as for NGC 973 (see Section 6.4.1), we determined an upper limit on the extent of the emitting region by convolving a set of gaussians with the PACS PSF and subtracting them from the horizontal profile. For NGC 4013, we find an upper limit on the central source's FWHM of $1.3''$, corresponding to a physical scale of ~ 120 pc.

Apart from this prominent central peak, the emission from the disc seems to be concentrated in a single ring-like or spiral structure. This is much more difficult to discern in the SPIRE maps, due to the poorer resolution.

6.4.5 NGC 4217

For NGC 4217, we assume a distance of 19.6 Mpc. The galaxy has a D_{25} diameter of $5.2'$ and is classified as an Sb or SAb sp type galaxy, showing HII emission regions. Having an inclination of 88.01° (Bianchi 2007), the galaxy is displaying a dust lane, visible along the entire disc and with an extensive vertical dust distribution (Howk & Savage 1999; Thompson et al. 2004), although we note that Alton et al. (2000a) consider this galaxy to be too highly inclined to make any unambiguous claims about extraplanar

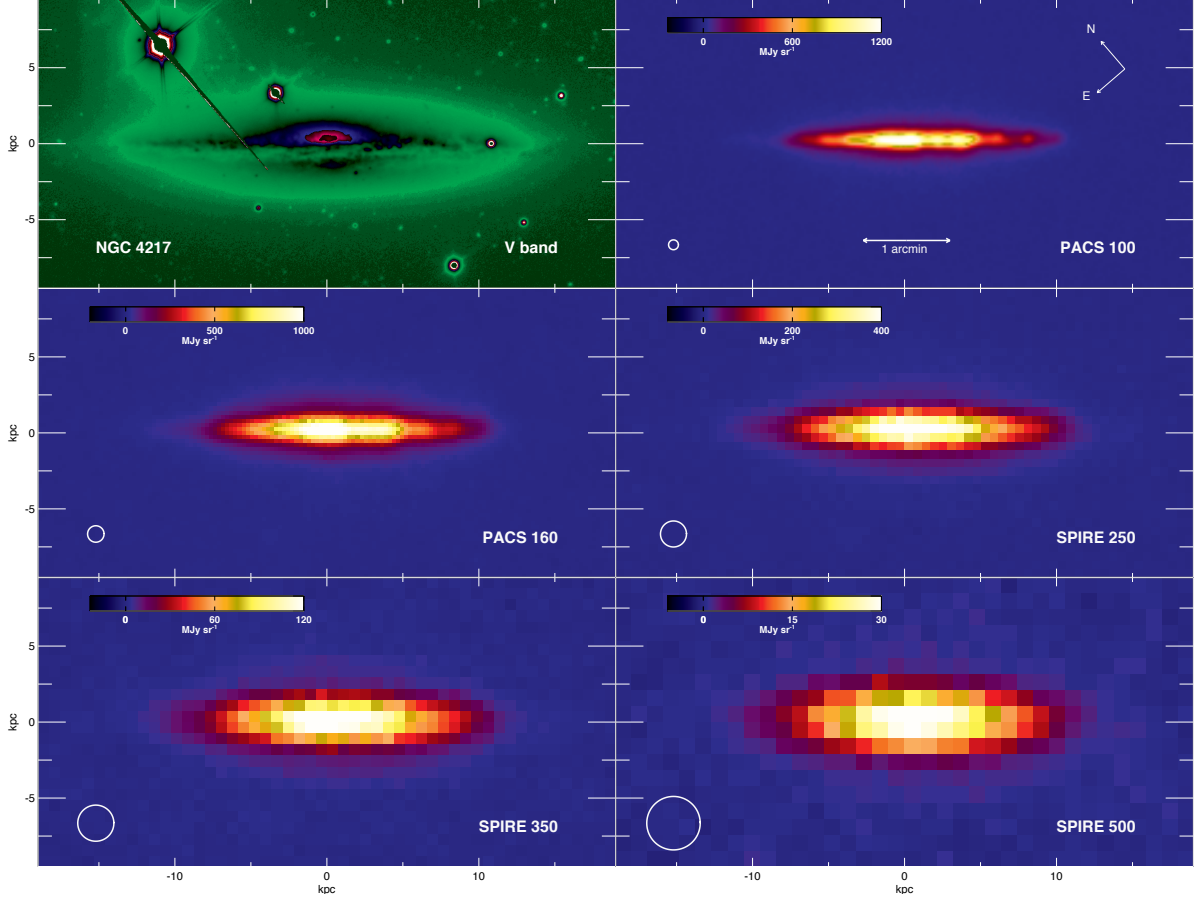


Figure 6.6: Optical V-band and *Herschel* PACS and SPIRE images for NGC 4217. The image sizes are about $6' \times 3'$.

dust. A global fit of extinction by the dust distribution to optical images was carried out in Bianchi (2007), giving a dust scalelength of $70''$ or 6.7 kpc, which is 75% larger than the stellar disc scalelength.

Compared to the other galaxies in the sample, the horizontal profiles for NGC 4217 are remarkably smooth: only the $100 \mu\text{m}$ profile — and the $160 \mu\text{m}$ one to a lesser extent — shows some small secondary peaks at $0.4'$ and $0.6'$ from the centre, and two more, less prominent, at $1'$ and $1.4'$, but all on the SW side. However, the overall behaviour is quite peculiar and differs between wavelengths. At $100 \mu\text{m}$, the profile first drops off from the centre outward, until about $1.6'$ on the SW side and about $1'$ on the NE side of the disc. At these points, a break in behaviour occurs and the slope of the profile becomes much steeper, up to about $2'$ on either side, where the background takes over. For the other wavelengths, the profiles have a slightly different character: on the SW side of the disc, they run more or less parallel to the $100 \mu\text{m}$ profile until the break in slope at about the same position, but beyond this point they are not as steep as the $100 \mu\text{m}$ profile and reach out to about $2.5'$. On the other hand, at the NE end of the disc

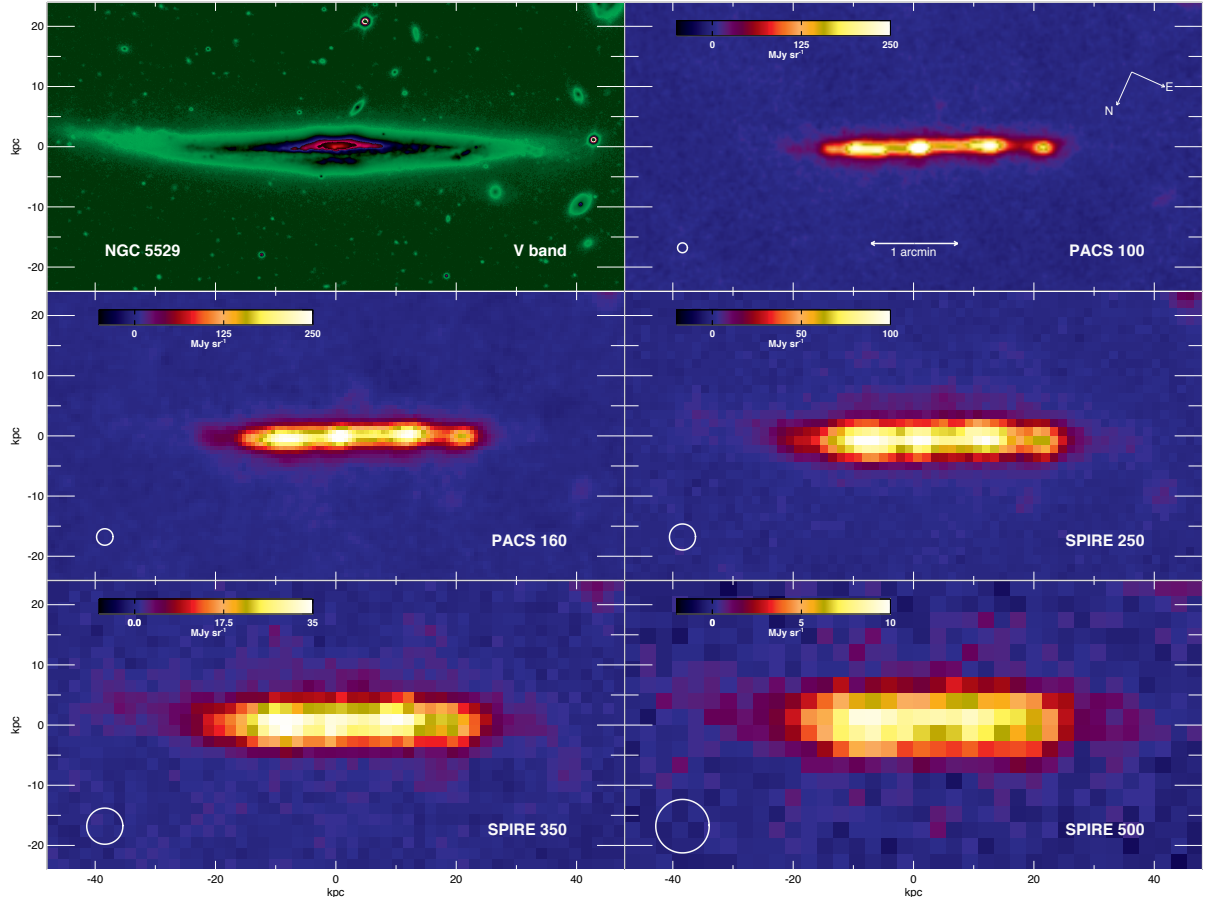


Figure 6.7: Optical V-band and *Herschel* PACS and SPIRE images for NGC 5529. The image sizes are about $6' \times 3'$.

they seem to have a single slope out to $2.5'$.

The exponential model we superimposed to the observed horizontal profile seems to be a good representation of the data, especially in the innermost regions. The PACS 100 μm map shows two clearly visible secondary peaks, along with one (possibly two) fainter structure(s), but due to the fact that all these are located on just one side of the disc (the SW end), lacking any clearly distinguishable counterparts on the other side, it would be very hard to identify any of these as a ring or spiral arm with any degree of certainty. Due to the worsening angular resolution, these structures can no longer be told apart at the longer wavelengths.

6.4.6 NGC 5529

With a distance of 49.5 Mpc, NGC 5529 has a D_{25} diameter of $6.35'$ and is classified as an Sc type galaxy (Xilouris et al. 1999). The system shows a clear warp (Sanchez-Saavedra et al. 1990, in POSS Blue and Red) and a box-shaped bulge (de Souza & Dos Anjos

1987). The fitted inclination is 86.94° (Bianchi 2007), exposing a very prominent dust lane (de Grijs & van der Kruit 1996) along the major axis as well as in the vertical direction (de Grijs & van der Kruit 1996). The dust distribution was previously modelled in Xilouris et al. (1999) and Bianchi (2007) based on a global fit to optical extinction data, both determining a dust scalelength of $50''$, corresponding to 11.7 kpc (Bianchi 2007) or 11.9 kpc (Xilouris et al. 1999), which is about 35% (Bianchi 2007), respectively 50% (Xilouris et al. 1999), larger than their fitted stellar disc scalelength.

All PACS and the SPIRE 250 μm horizontal profiles have a clear central peak, along with two secondary peaks on the SE side at $0.8'$ and $1.5'$ from the centre and another secondary peak around $0.6'$ on the other side, the latter having a small plateau at PACS wavelengths. On the other hand, the other SPIRE horizontal profiles show no apparent central peak and only marginally differentiable peaks at the locations of the secondaries visible at the previous wavelengths. At SPIRE wavelengths, the emission in the central region remains more or less at a plateau out to around $1.5'$ on the SE side and to around $0.8'$ on the NW side, after which the profiles drop off rather sharply out to $2'$ on both sides, then reach another plateau at a reduced level, and finally fall steeply around $2.5'$ from the centre. For the PACS wavelengths, the profile behaviour is quite different: while the NW side can be interpreted as having a constant plateau underneath the secondary peak out to $0.8'$ from the centre, the SE side shows a shallow but clear slope out to about $1.6'$ from the centre. Beyond these edges, the PACS profiles drop off sharply out to about $2'$ on either side.

A single dust disc with an exponential distribution does not suffice to describe the FIR emission for this galaxy, as can be concluded from the horizontal profiles, mostly due to the central regions where the profiles are relatively flat. The mentioned secondary peaks can be clearly distinguished in the images up to 250 μm , but given their differing positions on either side of the central peak, one would tend to conclude it is more likely that it concerns a spiral structure rather than a few ring-like structures. A final remark on this galaxy is the possibility of a warp in the dust disc: at least at 100 μm , the outer secondary peaks (at $1.4'$ on the SE side and at $0.6'$ on the NW side) are collinear with the centre, but the brightest secondary peak (at $0.8'$ from the centre on the SE side of the disc) seems to be concentrated slightly to the SW side of the major axis. This could mean that this brightest secondary peak lies just outside the main dust disc, but perhaps a more likely possibility is that the whole dust disc has a position angle different from the adopted V-band value, with the $0.8'$ (SE) and $0.6'$ (NW) secondary peaks more or less collinear with the bulge, while the outer peak at $1.4'$ (SE) is warped outside of the dust disc. It should be pointed out that Bianchi (2007) notes a slight warp in the outer parts of the disc is clearly visible in the optical observations.

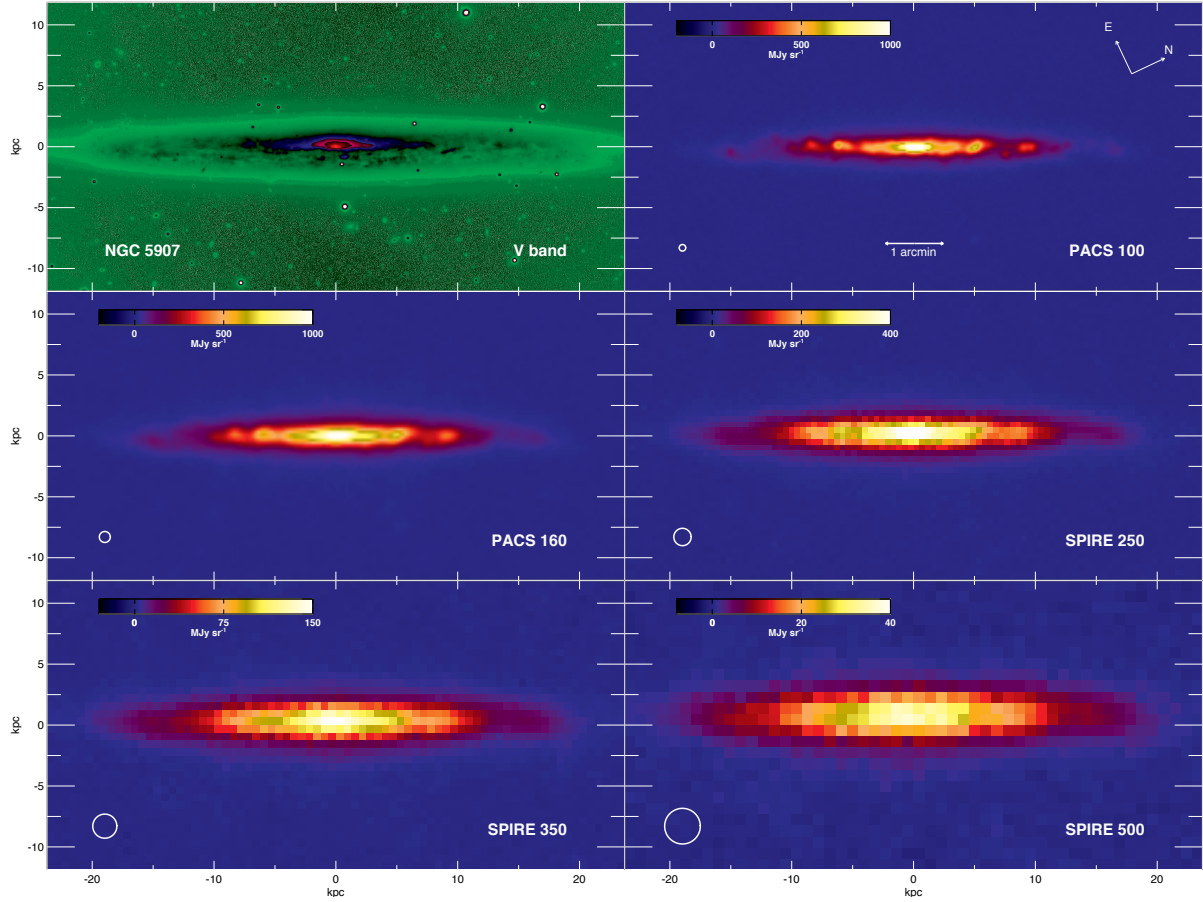


Figure 6.8: Optical V-band and *Herschel* PACS and SPIRE images for NGC 5907. The image sizes are $10' \times 5'$.

6.4.7 NGC 5907

The galaxy NGC 5907 is at a distance of 16.3 Mpc and has a D_{25} diameter of $12.77'$. It is considered to be either an Sc (Xilouris et al. 1999) or an SA(s)c type galaxy and it has HII regions. According to Sanchez-Saavedra et al. (1990, in POSS Blue and Red) it has a barely perceptible warp, but the stellar (Morrison et al. 1994) and HI (Sancisi 1976; Shang et al. 1998) warps are definitely both bending in the same direction. Sandage & Bedke (1994) claim the galaxy has a thin disc with the central bulge absent, but a bulge was fitted well with a modified Hubble profile by Barnaby & Thronson (1992), although resulting in a bulge-to-disc luminosity ratio of only 0.05 in the H-band. The inclination for the system has a fitted value of $87.2^\circ \pm 0.2^\circ$ (Xilouris et al. 1999). The dust lane extends from the centre out to the edges along the major axis, and although Howk & Savage (1999) state that the galaxy has no detectable vertically extended dust or ionised gas, Alton et al. (2000a) claim this galaxy to be insufficiently edge-on to make any definite statements about extraplanar dust. The dust distribution has been previously modelled using global fits to the dust lane extinction in optical images (Xilouris

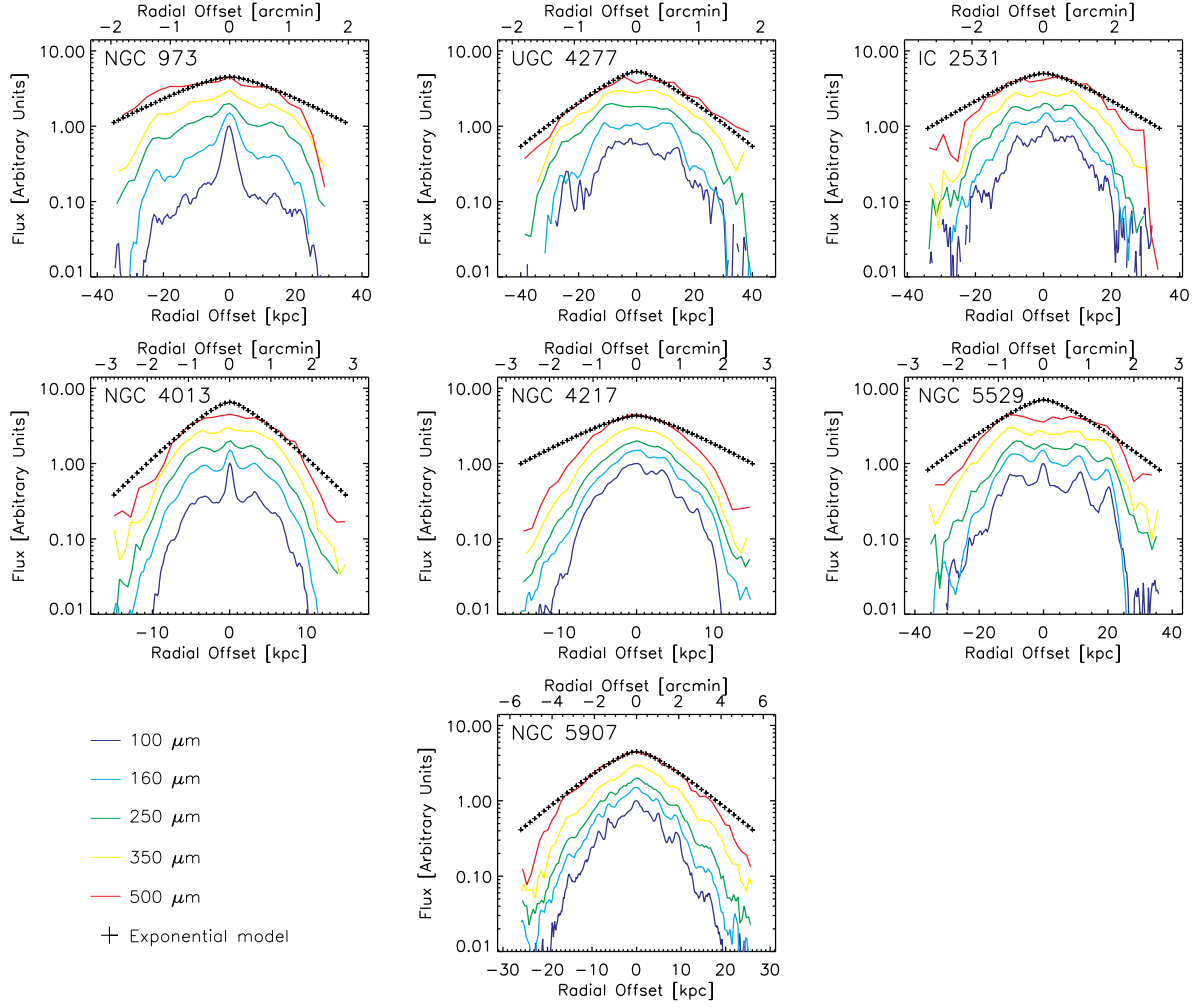


Figure 6.9: The horizontal profiles for the galaxies in the sample, at *Herschel* wavelengths. An arbitrary offset was introduced between different wavelengths for the sake of visualisation. A corresponding profile resulting from the double-exponential model is overplotted with black crosses, to compare with the commonly adopted description of the spatial dust distribution. The profiles are oriented as in the maps.

et al. 1999), leading to a dust scalelength of $100''$ or 7.8 kpc, which is about 10% larger than the corresponding stellar disc scalelength.

Up to $250 \mu\text{m}$, the horizontal profiles display a number of clear secondary peaks on each side of the central peak, more or less symmetrically positioned. All but the $100 \mu\text{m}$ profile have roughly the same behaviour, with a single slope from the centre out to around $3.5'$ from the centre and then a steeper slope out to about $5'$ to $6'$ on either side, although the $500 \mu\text{m}$ profile shows a slightly shallower decline in the central area up to about $3'$ on both sides. The PACS $100 \mu\text{m}$ has a steeper drop-off beyond $2'$ from the centre out to around $4'$ on either side, where the background starts to dominate.

The exponential dust distribution is in this case a very good description of the FIR hor-

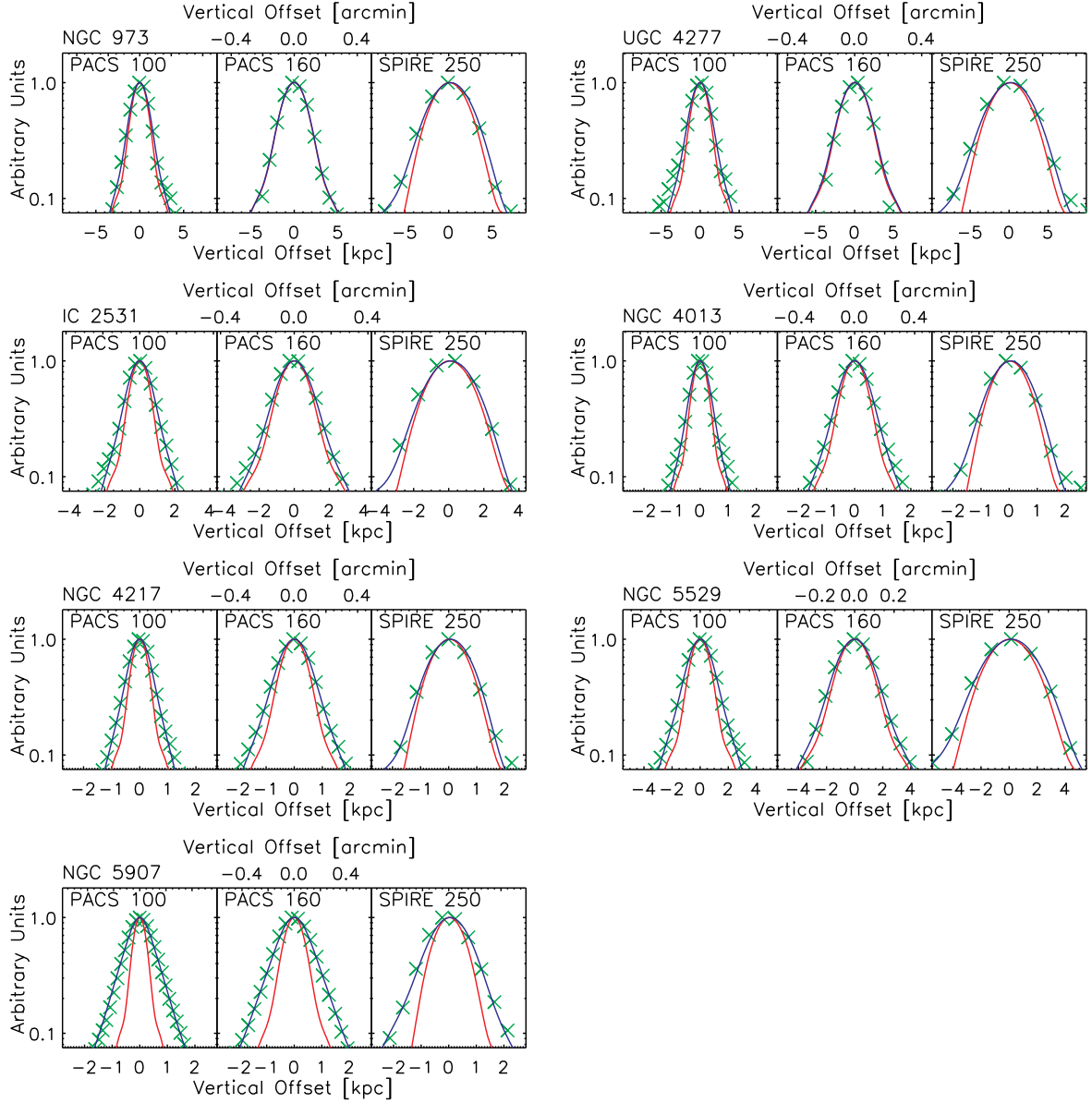


Figure 6.10: Vertical, normalised, profiles at 100, 160 and 250 μm are plotted as green crosses, to which we superimpose, as a blue line, a fit with an exponential profile, convolved with the *Herschel* beam at the appropriate wavelength (depicted here as a red line).

izontal profiles, at least at SPIRE bands, also considering the disc is possibly truncated. The fact that there are several secondary peaks distinguishable at PACS wavelengths on either side of the centre, could be indicative that a spiral structure is more likely than a dust ring.

6.5

Vertical dust distribution

In this Section, we discuss the vertical distribution of the FIR/sub-mm emission in the *HEROES* galaxies. As mentioned in the Introduction, edge-on spiral galaxies are the only systems where we can directly infer the vertical distribution of the dust. The presence of a spatially resolved vertical profile in the FIR for an edge-on galaxy might be related to dust above the galactic disc (extra-planar dust), ejected from the galactic plane. Whether such “dusty thick discs” are a common feature in spiral galaxies, and what the correlation is with other physical properties, is not yet well understood. Furthermore, studying the mechanisms that are responsible for dust ejection can shed new light on the transport of ISM from the galactic plane to higher latitudes.

Studying the vertical distribution of dust can be done in two ways: either by analysing the absorption in optical images, or by directly studying the vertical distribution of the FIR/sub-mm emission. Radiative transfer modelling efforts of optical images of edge-on spiral galaxies typically result in a dust disc with a vertical scaleheight that is approximately only half the vertical scaleheight of the stellar distribution, implying that the dust has a smaller vertical velocity dispersion than the stars. Deep optical imaging, however, has shown significant amounts of extraplanar dust in several edge-on spirals (e.g. Howk & Savage 1999; Alton et al. 2000b; Thompson et al. 2004). This dust at high latitudes can be interpreted as either expelled outflowing material from the galaxy if it is present, or infalling intergalactic matter otherwise (Howk 2012). Small dust grains and polycyclic aromatic hydrocarbons (PAHs), both relatively warm, have been traced in direct emission up to several kpc above the disc plane of some edge-on spirals (e.g. Irwin & Madden 2006; Irwin et al. 2007; Kamphuis et al. 2007; Whaley et al. 2009).

As already explained in Section 6.2.3, we have, first of all, reprojected all the images so that the major axes of the galaxies are parallel to the x axes of the maps (see Figure 6.2 to 6.8). We subsequently extracted vertical profiles at PACS and SPIRE wavelengths for each galaxy. To do so, we first selected the area, along the horizontal extent, where any pristine emission from the galaxy could be securely detected. We then summed all the pixel values along the image x coordinate (along the major axis) and normalised the resulting profiles. The resulting vertical profiles are shown in Figure 6.10.

Table 6.4: Scaleheight (h_z) values and related uncertainties as derived from the vertical profile fitting at 100, 160 and 250 μm , together with the physical scale of the PSF, given at each wavelength. The second to last column contains the vertical scaleheight of the dust as derived from radiative transfer fits to V-band images by Xilouris et al. (1997, 1999) or Bianchi (2007) (for the two galaxies in common between both samples, we list the average value). The last column contains the scaleheight that would result from an infinitesimally thin exponential disc, observed with the actual inclination of the galaxy (see text for a detailed explanation). All scaleheights and FWHM values are expressed in kpc.

Galaxy	$h_z[100]$	FWHM	$h_z[160]$	FWHM	$h_z[250]$	FWHM	$h_z[\text{opt}]$	$h_z[\text{incl}]$
NGC 973	$0.36^{+0.16}_{-0.21}$	2.09	$0.14^{+0.38}_{-0.13}$	3.41	$0.94^{+0.65}_{-0.92}$	5.41	0.59	0.21
UGC 4277	$0.48^{+0.36}_{-0.47}$	2.51	$0.30^{+0.30}_{-0.30}$	4.08	$1.09^{+1.02}_{-1.07}$	6.48	0.25	0.44
IC 2531	$0.33^{+0.11}_{-0.11}$	1.23	$0.33^{+0.15}_{-0.24}$	2.00	$0.44^{+0.37}_{-0.43}$	3.17	0.38	0.17
NGC 4013	$0.14^{+0.03}_{-0.03}$	0.62	$0.21^{+0.05}_{-0.05}$	1.02	$0.29^{+0.11}_{-0.14}$	1.61	0.20	0.03
NGC 4217	$0.21^{+0.02}_{-0.02}$	0.66	$0.27^{+0.04}_{-0.04}$	1.07	$0.26^{+0.10}_{-0.12}$	1.70	0.38	0.43
NGC 5529	$0.46^{+0.10}_{-0.10}$	1.64	$0.42^{+0.17}_{-0.23}$	2.67	$0.74^{+0.40}_{-0.72}$	4.24	0.39	1.16
NGC 5907	$0.41^{+0.04}_{-0.04}$	0.56	$0.42^{+0.04}_{-0.04}$	0.90	$0.45^{+0.10}_{-0.10}$	1.43	0.16	0.69

We modelled these vertical profiles with an exponential function of the form:

$$\Sigma_{\text{ver}}(z) = \frac{1}{2h_z} \exp\left(-\frac{|z|}{h_z}\right) \quad (6.4)$$

as appropriate for an exactly edge-on, double-exponential disc (see Equation 6.5). Before fitting this vertical profile to the observed data, we first convolved it with the *Herschel* beams at the appropriate wavelength. The latter were obtained from the circularised PSF images described in Aniano et al. (2011). To obtain the one-dimensional beams, we averaged the two-dimensional PSFs along one direction, adopting a similar procedure as that followed to produce the vertical profiles. At this point we searched the optimal value of h_z that would best reproduce the observed profile, by evaluating a standard χ^2 function. $N = 9$ to 15 pixels were used to adequately sample the observed vertical profiles, depending on the wavelength. Uncertainties on the value of the scaleheight h_z were also derived from the χ^2 probability distribution. The results of these fits are listed in Table 6.4, together with the value of the PSF in linear units for each of the bands, and with the value of the vertical scaleheight derived from radiative transfer modelling at optical wavelengths. We consider that a galaxy has a spatially resolved vertical profile when the profile is not dominated by the telescope beam, that is when the deconvolved scaleheight value we derive from the profile fitting is *not* consistent with zero at the 5σ level.

Before the values of the scaleheight in different wavelengths can be compared with

each other, and with the scaleheight derived from radiative transfer modelling, a number of issues need to be considered.

A first obvious concern when comparing the dust scaleheights derived in the different bands is the strongly different resolution of the images. Even at the shortest wavelength we have observed, $100\ \mu\text{m}$, the FWHM of the observations is $6.8''$ and it dominates the vertical distribution. This is in vast contrast with the optical images used for the radiative transfer modelling, which have $\sim 1''$ resolution. It can hence not be expected that both methods give comparable results.

A second point to take into account is the effect of the inclination on the apparent vertical structure. For the scaleheights derived from radiative transfer modelling, the inclination of the dust disc has been taken into account (the inclination is always one of the crucial free parameters in the fitting procedure). In our simple fitting modelling approach of the *Herschel* profiles, we implicitly assume a perfectly edge-on disc. As the dust discs in spiral galaxies are extremely thin and radially extended, even a small deviation from a perfect edge-on orientation could strongly affect the observed “vertical” structure of edge-on galaxies in the FIR/sub-mm maps. Consider first a double-exponential disc, described by the three-dimensional density distribution (6.1) and the dust surface density distribution (6.2) when viewed exactly edge-on. When we collapse the surface density distribution in the horizontal direction and normalise the resulting expression, we recover a simple exponential function as the vertical profile

$$\Sigma_{\text{ver}}(y) = \frac{1}{M_d} \int_{-\infty}^{\infty} \Sigma(x, y) dx = \frac{1}{2h_z} \exp\left(-\frac{|y|}{h_z}\right) \quad (6.5)$$

Now assume a system in which the dust is distributed in an infinitely thin, exponential disc, i.e. with a density distribution like Equation (6.1) with $h_z \rightarrow 0$,

$$\rho(R, z) = \frac{M_d}{2\pi h_R} \exp\left(-\frac{R}{h_R}\right) \delta(z) \quad (6.6)$$

When this disc has an inclination i , its mass surface density distribution projected on the sky becomes

$$\Sigma(x, y) = \frac{M}{2\pi h_R^2 \cos i} \exp\left(-\frac{1}{h_R} \sqrt{x^2 + \frac{y^2}{\cos^2 i}}\right) \quad (6.7)$$

When we collapse this surface density profile in the horizontal direction and normalise, we find

$$\Sigma_{\text{ver}}(y) = \frac{1}{\pi h_R \cos i} \left(\frac{|y|}{h_R \cos i}\right) K_1\left(\frac{|y|}{h_R \cos i}\right) \quad (6.8)$$

When an infinitesimally thin exponential disc with radial scalelength h_R is not exactly

edge-on, it will hence give rise to a vertical profile that is extended, which could be falsely interpreted as an intrinsic vertical distribution of an exactly edge-on spiral galaxy. To determine the importance of this inclination effect, we estimate the exponential scaleheight h_z that would correspond to the vertical profile (6.8), by requiring the FWHM of both distributions to be equal. For the expression (6.8) we find

$$\text{FWHM} \approx 2.5143 h_R \cos i \quad (6.9)$$

whereas the exponential profile (6.5) gives

$$\text{FWHM} = 2 \ln 2 h_z \approx 1.3863 h_z \quad (6.10)$$

and therefore

$$h_z \approx 1.8137 h_R \cos i \quad (6.11)$$

In the last column of Table 6.4 we list the apparent scaleheight obtained using this formula for the seven *HEROES* galaxies, based on the disc scalelength h_R and inclination i derived from the radiative transfer modelling. By looking at the values reported in this table, together with the profiles in Figure 6.10, and taking into account the cautions expressed above, we can draw different conclusions regarding the vertical structure of the *Herschel* images. For four out of the seven galaxies in the sample (NGC 973, UGC 4277, IC 2531 and NGC 5529), the vertical profile is not resolved at the 5σ level, even at the shortest wavelength. It is not a coincidence that these four galaxies are the most distant ones in the sample.

For two galaxies in the sample, NGC 4217 and NGC 5907, the vertical profile is resolved at the 10σ level, in the PACS 100 and 160 μm bands. Remarkably, in both cases the scaleheight of the dust derived from the PACS observations is not in agreement with the values derived from the radiative transfer fitting: in the case of NGC 4217 the FIR scaleheight is substantially smaller than the value derived by Bianchi (2007), whereas for NGC 5907 it is more than twice as large as the value obtained by Xilouris et al. (1999). The key to these differences is the inclination of the galaxies: they are both more than 2 degrees from exactly edge-on. At these inclinations, the apparent vertical structure of galaxies can be explained as an infinitely thin exponential disc projected on the sky, as can be seen from the last column of Table 6.4.

Finally, for NGC 4013, we resolve the vertical structure marginally at the 5σ limit in the PACS 100 and 160 μm bands. With an inclination of 89.7° , this galaxy has the closest to exactly edge-on orientation of all galaxies in the sample, and the vertical structure cannot be due to the projection along the line-of-sight of the radial structure. This is hence the only galaxy in the sample in which we find reliable evidence for vertically resolved

dust emission. Interestingly, Howk & Savage (1999) found evidence for extra-planar dust from the analysis of extinction features in optical images for NGC 4013. The FIR-derived values for the scaleheight are in good agreement with the value derived from radiative transfer modelling by Bianchi (2007).

It is intriguing to see that the scaleheight seems to increase with increasing wavelength. It is tempting to interpret this as a natural consequence of the decreasing dust temperature that is expected if one goes to gradually higher distances above the plane of the galaxies. However, radiative transfer models have shown that vertical gradients in T due to diffuse dust heating are very shallow anyway (see e.g. Figure 3 in Bianchi et al. 2000a). Furthermore, this result is most probably driven by the size of the PSF's FWHM which increases as a function of the wavelength. Thus, it is normal that the best fit value is somehow dependent on this (the same effect is also seen for the galaxies where we do not properly resolve the vertical structure).

6.6

Determination of the dust masses

To determine the total mass of the dust in the galaxies, we follow two different methods. Firstly, we use the model parameter results from fitting dust distribution models to V-band images due to extinction as given in Xilouris et al. (1997, 1999) and Bianchi (2007), but scaled to the distances used here. In the future we will repeat this approach and model all galaxies homogeneously with a single, oligochromatic fitting tool, Fit-SKIRT (De Geyter et al. 2013), which we have developed on top of the SKIRT code. For the second method, we determine the dust mass by fitting simple modified black-body models to the global *Herschel* fluxes.

6.6.1 Dust masses from radiative transfer fits

Xilouris et al. (1997, 1999) and Bianchi (2007) determined the intrinsic distribution of stars and dust in all *HEROES* galaxies by fitting radiative transfer models to V-band images. In their models, the dust mass density distributions are smooth, axisymmetric models with the double-exponential behaviour defined earlier in equation (6.1). Rather than the total dust mass, the quantity of dust in these models is usually parametrised by the face-on optical depth along the central line-of-sight. The connection between dust mass and the face-on optical depth follows directly from the definition of the latter quantity,

$$\tau_{\lambda}^f = \int_{-\infty}^{\infty} \kappa_{\lambda} \rho(0, z) dz \quad (6.12)$$

Table 6.5: Derivation of the dust masses for the galaxies in our sample. The second, third and fourth columns contain horizontal scalelength h_R , the vertical scaleheight h_z , and the face-on optical depth τ_V^f of the dust as derived from radiative transfer fits to V-band images (the scalelength and scaleheights have been rescaled to the distances adopted within *HEROES*). The fifth column is the optically determined dust mass calculated from these values using equation (6.14). The sixth column contains the reference of the radiative transfer fit: X97 (Xilouris et al. 1997), X99 (Xilouris et al. 1999) or B07 (Bianchi 2007). Dust temperature and dust mass as derived from a modified black-body fit to the *Herschel* data are reported in the following columns, while the last one is the far infrared luminosity.

Galaxy	h_R (kpc)	h_z (kpc)	τ_V^f	$\log M_d^{\text{opt}}$ ($M_\odot$)	ref	T_d (K)	$\log M_d^{\text{FIR}}$ ($M_\odot$)
NGC 973	16.33	0.59	0.48	8.17	X97	20.0 ± 0.6	8.11 ± 0.07
UGC 4277	12.52	0.25	0.49	7.95	B07	17.3 ± 0.6	8.31 ± 0.09
IC 2531	13.68	0.38	0.30	7.81	X99	18.5 ± 0.3	8.04 ± 0.04
NGC 4013	3.93	0.21	0.67	7.08	X99	21.5 ± 0.4	7.63 ± 0.04
	2.67	0.19	1.46	7.08	B07		
NGC 4217	6.72	0.38	1.26	7.81	B07	22.1 ± 0.4	7.85 ± 0.03
NGC 5529	11.87	0.52	0.65	8.02	X99	19.4 ± 0.4	8.32 ± 0.05
	11.66	0.26	0.68	8.03	B07		
NGC 5907	7.84	0.16	0.49	7.54	X99	20.0 ± 0.3	8.12 ± 0.03

with κ_λ the extinction coefficient for the dust at wavelength λ . Combining this expression with the density distribution (6.1) of the double-exponential disc model gives us

$$M_d = \frac{2\pi \tau_\lambda^f h_R^2}{\kappa_\lambda} \quad (6.13)$$

Adopting the value $\kappa_V = 2619 \text{ m}^2 \text{ kg}^{-1}$ for the V-band dust extinction coefficient in the interstellar medium (Draine 2003b) leads to the formula

$$M_d = 1.148 \times 10^6 \tau_V^f \left(\frac{h_R}{\text{kpc}} \right)^2 M_\odot \quad (6.14)$$

which is virtually identical to Equation (11) from Xilouris et al. (1997). When we substitute the values for h_R and τ_V^f as derived by Xilouris et al. (1997, 1999) and Bianchi (2007), we obtain the dust masses listed in the fifth column of Table 6.5, where we added the superscript “opt” to indicate that it refers to the dust mass determined from radiative transfer fits to optical images. For the two galaxies in common between the samples used in the aforementioned works, NGC 4013 and NGC 5529, the derived dust mass estimates are nearly identical. This is particularly remarkable for NGC 4013, since the values for τ_V^f and h_R obtained by the radiative transfer fits are quite different. This

is due to a degeneracy in the radiative transfer modelling of edge-on spiral galaxies, which has been noted by Bianchi (2007) and De Geyter et al. (2013). Systems with a large face-on optical depth and a small dust scalelength and systems with a small face-on optical depth and a large dust scalelength can both result in similar edge-on optical depth and hence dust lanes of similar depths. Fortunately, the total dust mass, which is a combination of these parameters, is rather insensitive to this degeneracy.

6.6.2 Global SED fitting

We also determined the dust masses for the galaxies in our sample by fitting a simple modified black-body model to the PACS and SPIRE data, i.e.

$$F_\nu = \frac{M_d \kappa_\nu B_\nu(T_d)}{D^2} \quad (6.15)$$

where M_d is the dust mass, B_ν is the Planck function, T_d is the dust temperature, D is the distance to the galaxy and κ_ν is the dust emissivity. As customary, we assumed a power-law dust emissivity in the FIR/sub-mm wavelength range,

$$\kappa_\nu \propto \nu^\beta \quad (6.16)$$

and we fix the value of the emissivity to $\kappa_\nu = 0.192 \text{ m}^2 \text{ kg}^{-1}$ at $350 \mu\text{m}$. The fits were done by performing a χ^2 minimisation using a simple gradient search method, with M_d and T_d as free parameters, with β fixed to a value of 1.8. Error bars on the fitted parameters were derived using a bootstrapping method, as follows: when the best-fit parameters (T_d , M_d and β) are found, 200 new sets of datapoints are created by randomly drawing a value from the observed fluxes, lying within the observed errorbars. A best fit is searched for each one of these new artificial datasets: 16% of the best fit models having the lower and higher parameters values are discarded, and uncertainties are then taken as the differences between the best fit solution and the extreme values.

The results of these modified black-body fits are shown in Figure 6.11 and listed in the last three columns of Table 6.5 (the dust masses as derived from the SED fits are denoted as M_d^{FIR} to make the distinction with the optically determined dust masses). Had we left the emissivity index, β , as a free parameter, we would have found an average value of $\langle\beta\rangle = 1.73 \pm 0.36$, very close to the value we have used for the fits. Using the same value for the emissivity index allows us to compare, in a consistent manner, the dust mass values we derive. Furthermore, this value of β and the average temperature $\langle T_d \rangle = (19.8 \pm 1.6) \text{ K}$, that we obtain, are very typical values for the interstellar dust medium in spiral galaxies (e.g Dunne et al. 2011; Davies et al. 2012; Smith et al. 2012;

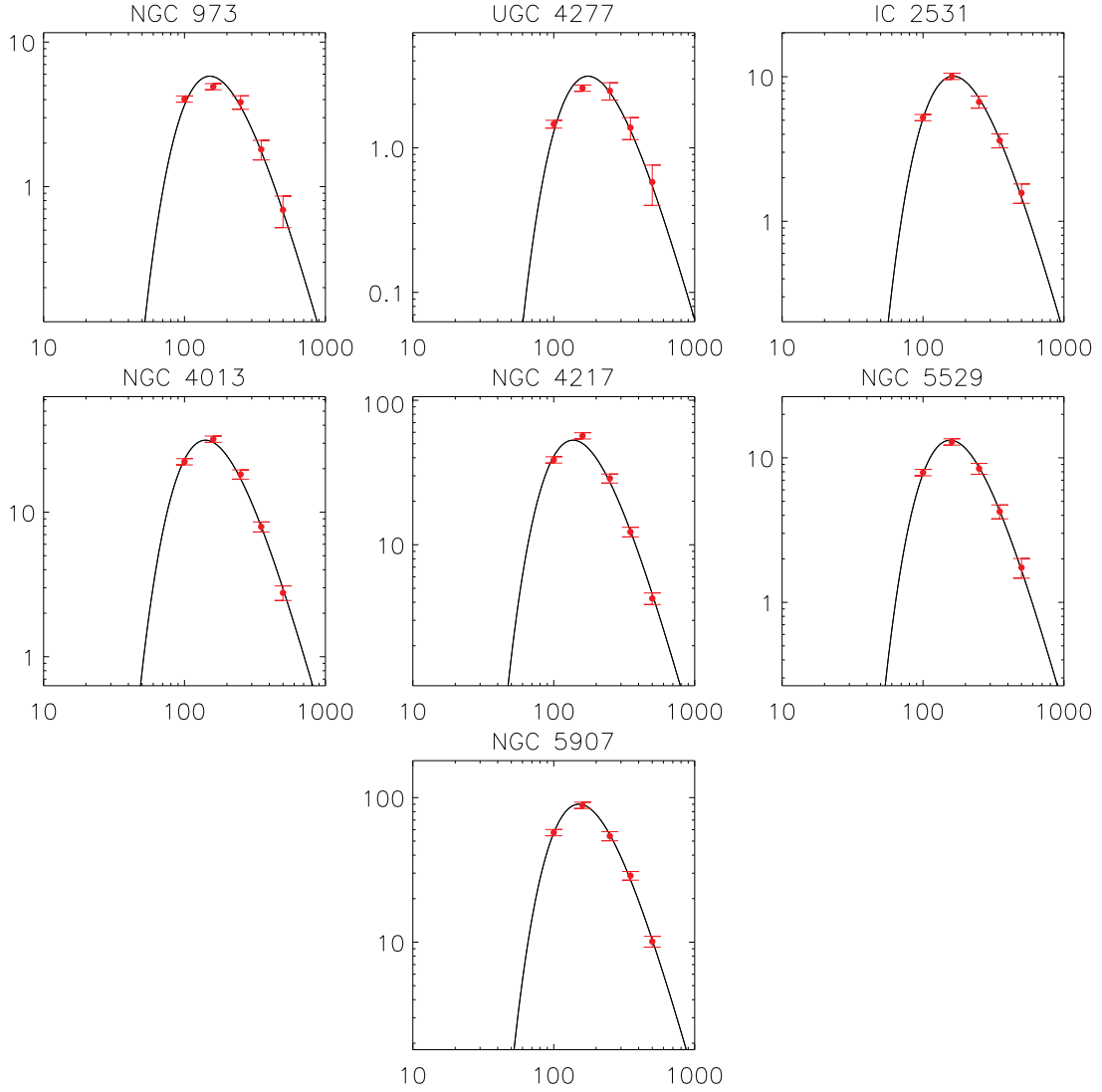


Figure 6.11: SED fitting to the *Herschel* fluxes (here depicted as red diamonds) for all *HEROES* galaxies. A modified, single temperature black-body model (black line) is adopted. The y axes are in units of Jansky while the x axes are in micron.

Boselli et al. 2012; Galametz et al. 2012). As the latter model only reproduces datapoints longwards of $100 \mu\text{m}$, the dust mass values we give do not take into account the possible presence of warmer dust, whose signature would show up at shorter wavelengths. The latter, anyway, constitutes a minor fraction of the total dust mass (see, e.g. Smith et al. 2010).

6.6.3 Comparison of optical and FIR dust masses

When we compare the total dust masses as they were determined from both methods described in the previous subsections, we see a clear difference between the different mass estimates, with the ones derived from radiative transfer fits of the optical images

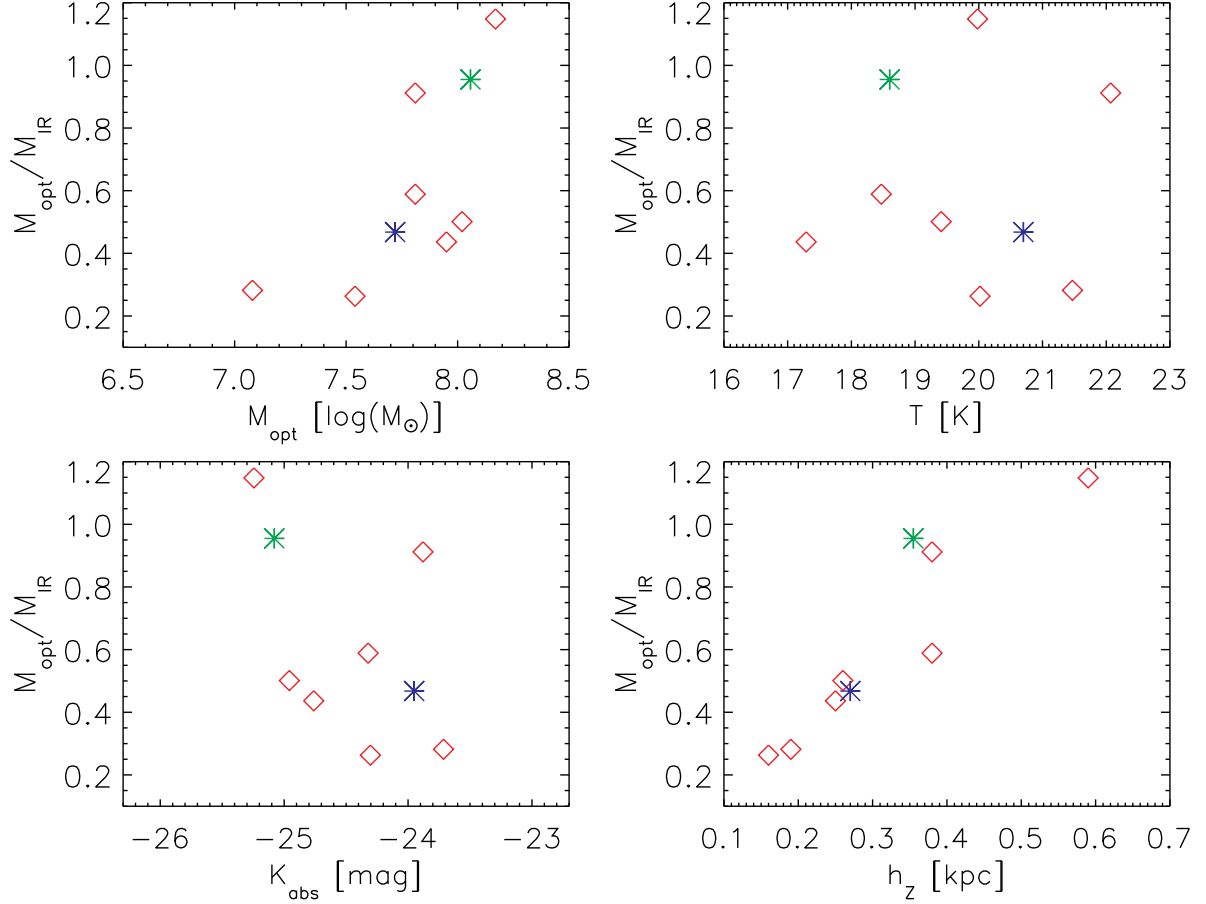


Figure 6.12: In these four panels we compare the difference in the values of the dust mass as computed from radiative transfer modelling of optical data and as computed from black-body fitting of *Herschel* datapoints, with various physical quantities: the (optically derived) mass of dust, the dust temperature, the absolute K-band magnitude and the dust scaleheight. The starred points correspond to two other well known edge-on galaxies not included in our sample: NGC 891 (blue) and NGC 4565 (green).

being consistently smaller than the dust masses derived from the far-infrared emission. Only for NGC 973, both dust masses are in agreement, while for all other galaxies the optically determined dust mass significantly underestimates the FIR dust mass, by a factor of up to about four. Such a mass discrepancy was previously found in a number of edge-on spiral galaxies (Popescu et al. 2000a; Misiriotis et al. 2001; Alton et al. 2004; Dasyra et al. 2005; Bianchi 2008; Baes et al. 2010b; De Looze et al. 2012a). Our new observations, which also cover the sub-mm part of the SED and hence allow a solid determination of the bulk of the cold dust, confirm the results of these studies.

In order to investigate the underlying mechanism of this discrepancy, we look for possible relations between the ratio of the optical and FIR dust masses and a number of global galaxy properties. Figure 6.12 plots the $M_{\text{d}}^{\text{opt}}/M_{\text{d}}^{\text{FIR}}$ as a function of dust mass, dust temperature, K-band absolute magnitude (used as a proxy for stellar mass), and

dust vertical scaleheight. To increase the statistics, we include two additional notorious edge-on spiral galaxies in this figure, i.e. the prototypical edge-on spiral NGC 891 (blue asterisk) and NGC 4565, also known as the Needle Galaxy (green asterisk). To determine the FIR dust mass, we have used *Herschel* fluxes from Bianchi & Xilouris (2011) and De Looze et al. (2012a), respectively, and a similar fitting technique was used as for the *HEROES* galaxies. Optical dust masses were taken from radiative transfer modelling from Xilouris et al. (1998) and Alton et al. (2004). We have assumed distances of 9.5 and 16.9 Mpc for NGC 891 and NGC 4565, respectively.

Looking at Figure 6.12, we see no correlation between the dust mass discrepancy and the dust mass, stellar mass or dust temperature. Interestingly, we do find a trend between the dust mass discrepancy and the dust scaleheight as derived from radiative transfer fits to the optical images. To understand this trend, we note that the dust mass computed from extinction in optical images is only sensitive to the smoothly distributed fraction: in fact, the physical size of the dense, optically thick molecular clouds often hosting regions of active star formation, is too small for being detected by optical observations even for such relatively nearby galaxies, as those of the *HEROES* sample are. The net effect is that these small clumpy regions do not contribute to the global optical extinction at all. Their presence can only be revealed from the thermal emission of the dust they contain, showing up in the FIR (see, e.g., Popescu et al. 2000a). Hence, one of the possible interpretations of this dust mass discrepancy is that this ratio would be a measure of the clumpiness of the dust fraction of the ISM in a galaxy. A correlation between this difference and the scaleheight of dust would imply that the thinner the dust disc is, the clumpier its structure is. With only 9 objects being considered, one of which not lying perfectly on the correlation, we cannot be conclusive on this point, even though our analysis hints at a real relation, and it is furthermore supported by a Spearman correlation coefficient of 0.92.

6.7

Discussion and concluding remarks on *HEROES*

We have presented *Herschel* observations of a sample of seven edge-on spiral galaxies within the *HEROES* project. This work is the first one of a series of papers aiming at a systematic study of the properties of dust, and its relation to the stellar and gas components, in edge-on spiral galaxies. Here we have presented FIR and sub-mm data obtained with the *Herschel Space Observatory*, describing and analysing both the morphology and the horizontal and vertical distribution of dust.

We have measured the global FIR/sub-mm fluxes of the galaxies in the PACS and SPIRE bands using aperture photometry. We have compared the *Herschel* fluxes with

IRAS, *ISO*, *Akari* and *Planck* fluxes at similar wavelengths. We find excellent agreement between *Herschel* on the one side and *IRAS*, *ISO* and *Planck* on the other side. The only exception is NGC 5907, where both the *IRAS* 100 μm and the *ISO* 160 μm fluxes underestimate the PACS fluxes. We argue that this disagreement might be due to the large extent of this galaxy, which is spatially resolved even at the coarse resolution of *IRAS* and *ISO*. When we compare the PACS 160 μm fluxes with the *Akari* 160 μm fluxes, we find a strong inconsistency, with the *Akari* fluxes a factor two smaller, possibly due to a flux measurement effect.

We have described the resulting FIR morphology. A double exponential disc model for the dust distribution is capable of providing a good description of the observed IR and sub-mm profiles, especially at 500 μm , and as long as disc truncation is not taken into account. But at shorter wavelengths, the picture is more complicated: on the one hand, the occurrence of primary and several secondary peaks in the horizontal FIR/sub-mm profiles give a clear indication of morphological structure in the form of arms, rings or individual star formation complexes. On the other hand, the underlying horizontal data profiles (taking abstraction of the peaks) show a more complicated and varying behaviour across the horizontal span of the galaxies and especially at the PACS wavelengths. Quite interestingly, the two galaxies likely to host some nuclear activity, and classified as Seyfert 2 and LINER (NGC 973 and NGC 4013 respectively), are those showing the most prominent central peak at 100 μm , giving a hint of the presence of warmer or more concentrated dust. We have checked whether these peaks are compatible with a point-like emission, as expected — at these resolutions — for an AGN-like source. We found that the central peak is compatible with a Gaussian profile emission, imposing upper limits on the FWHM of the central source of ~ 450 and ~ 120 pc for NGC 973 and NGC 4013 respectively. These values are quite high if compared to the physical scales, of the order of few pc, found for the dusty tori of local low luminosity AGNs (see, e.g., Jaffe et al. 2004), whose emission peaks anyway around 30 to 50 μm (as IR modelling indicates; see e.g. Fritz et al. 2006; Stalevski et al. 2012). Our upper limits fit a picture where the intense UV/optical radiation field emitted by the central source would heat the dust to slightly larger scales, but to lower temperatures. This hypothesis has so far never been tested, but it is in principle verifiable by means of radiative transfer models.

By fitting an exponential model to the vertical profile of the *Herschel* images, we investigate whether we can detect vertically extended dust in edge-on galaxies. Evidence for extra-planar dust has been found before, either by means of extinction features in high-resolution optical images (Howk & Savage 1999; Alton et al. 2000b; Thompson et al. 2004) or through warm dust or PAH emission at mid-infrared wavelength (Irwin & Madden 2006; Irwin et al. 2007; Kamphuis et al. 2007; Whaley et al. 2009). Three

out of the seven galaxies show signatures of extended vertical emission at 100 and 160 μm at the 5σ level. For two of these three galaxies (NGC 4217 and NGC 5907), this vertically extended emission is most probably due to projection effects as a result of deviations from an exactly edge-on orientation. For the remaining galaxy, NGC 4013, the FIR/sub-mm emission seems truly resolved, and the inferred scaleheights are in agreement with the scaleheight independently derived from radiative transfer modelling of the optical images by Bianchi (2007). We find a hint of an increase in the scaleheight with FIR wavelength; rather than interpreting this as evidence that the dust temperature decreases with increasing distance above the plane of the galaxy, we argue that this is probably due to the limited and gradually worsening resolution of the *Herschel* images for increasing wavelengths.

Finally, total dust masses inferred from the optical extinction through radiative transfer models were compared with those determined from modified black-body fits to the FIR fluxes, and correlations with other physical and geometrical properties of the galaxies were searched for. While we do acknowledge that our sample — which we extended with two other well-known edge-on galaxies for this particular analysis — is quite limited to provide strong evidence, we found a hint of a correlation between the discrepancy between both dust masses and the vertical scaleheight of the dust: larger differences are found in galaxies with smaller scaleheights. If the discrepancy between the dust mass as derived from optical extinction and that calculated from IR emission is interpreted as a measure of the clumpiness of the ISM, this would be consistent with a picture where dust which is more “compressed” into the disc, would tend to be gathered in clumps more strongly, as opposed to a smoother, continuous distribution. While we are not aware of any study addressing this issue, this correlation will be tested by means of radiative transfer models. By exploiting a single, state-of-the-art radiative transfer code (SKIRT), coupled with a robust fitting algorithm explicitly targeted to the study of such edge-on systems (FitSKIRT, De Geyter et al. 2013), we should be able to at least confirm the presence of this trend. In fact, following the approach already used by Popescu et al. (2000a); Bianchi et al. (2000a) and more recently De Looze et al. (2012a), the FIR luminosity deficit always observed in models can be accounted for by including in the model, a posteriori, a dust emission component originating from very compact regions, hence invisible in optical extinction maps. The relative amount of this component with respect to the diffuse dust can then be compared to the dust scaleheight derived from the model itself and this, in turn, checked against our findings.

We gave a short introduction to the field of interstellar dust, its observed infrared thermal emission and its simulation in models in Chapter 1. This interstellar dust plays an important role in the physics and chemistry of the ISM of galaxies. It absorbs and scatters UV and optical radiation, rendering the correct interpretation of optical data rather difficult. Nearly all of the energy absorbed by dust is thermally radiated at MIR, FIR and sub-mm wavelengths. The overall goal of this thesis work was to perform a thorough investigation of the dust content in galaxies by studying its IR emission, using a dual approach. On the one hand, we take advantage of the new possibilities offered by the launch of the *Herschel Space Observatory*. This sensitive FIR/sub-mm space observatory has started off an exciting era of new, much more resolved and sensitive observations in a largely untouched part of the spectrum, opening up a grand potential for new discoveries. On the other hand, a tool to investigate these new observations, linking together the different ways in which dust is observable (attenuation/extinction in optical/NIR, emission in MIR/FIR) is invaluable. With this thesis, we aim to make significant progress in both areas, by extending the existing SKIRT tool with new capabilities, and by reducing and interpreting *Herschel* data. In this summary we provide a short overview of the results achieved in this thesis and present an outlook towards future research.

In Chapter 2, we presented an extended version of the SKIRT code. SKIRT is a 3D Monte Carlo radiative transfer code designed to investigate the properties of dust in galaxies, and has been continuously developed and extended over the last decade by the UGent group. One long awaited and crucial addition to the code is the self-consistent treatment of very small grains (VSGs) and polycyclic aromatic hydrocarbons (PAHs). While the dedicated code developed for this specific purpose still showed some problems and turned out to be prohibitively slow for 3D simulations, the use of the external DustEM code with a library approach showed to be a relatively efficient solution. A representative sample of the different interstellar radiation fields (ISRFs) within a simulation is taken and fed into DustEM, based on a 2D phase space of parameters, taking into account both the mean intensity of the ISRF and the absorption coefficient. The resulting dust emissivity profiles are then used to apply the dust

emission phase for all dust grid cells, depending on which 2D grid cell they occupy in the phase space. We can conclude that, given the appropriate use of optimisation techniques, it is possible to efficiently and accurately perform Monte Carlo radiative transfer simulations of arbitrary 3D structures of several million dust cells, including a full calculation of the NLTE emission by arbitrary dust mixtures. This significantly increases the number of applications where detailed radiative transfer modelling can be used.

The *Herschel Space Observatory* was introduced in Chapter 3, focussing on the photometry part of its PACS instrument. The standard data reduction pipeline was presented, along with slight modifications we applied to it, such as the use of customised masks for different tasks in the pipeline. Three different map-making algorithms were investigated: the first, MADmap was abandoned due to its high memory requirements and relatively poor quality maps at the time. The second, PhotProject was found to be mainly useful for the scientific exploitation of point sources, compared to Scanamorphos, which is more suited for extended sources, mainly because these sources are still badly affected by some remaining artifacts in PhotProject, such as negative bowls. With extensive testing and fine-tuning of the various steps in the data reduction pipeline and the input parameters for the mapping algorithms, we have optimised the resulting PACS maps for use within the *Herschel* observing programmes we are involved in.

Starting from Chapter 4, a few of these *Herschel* observing programmes, especially the large ones, were described. The first, HeViCS, performed a rather deep, large area survey of the Virgo Cluster, the closest galaxy cluster, to study various properties of dust in different locations of such a cluster. As a sanity check, different approaches of flux measurements were compared with similar literature data and with each other for a sample of galaxies, and they showed to be broadly consistent in most cases.

A number of scientific results were discussed, such as the apparent absence of any significant amount of cold dust causing a FIR excess beyond the synchrotron emission in M 87, putting an upper limit to the dust mass. SED fitting to the *Herschel* data points was used to determine dust temperatures and masses for the resolved dust analysis of a selection of spiral galaxies, as well as for a few detected star-forming dwarf galaxies. A sample of FIR selected bright galaxies was used to produce luminosity functions at the different *Herschel* wavelengths, and dust masses and temperatures were again calculated using SED fits. A number of asteroids, unrelated to the scientific objectives of the original proposal, were detected by their shifting positions between different scans of the same field, and identified. HeFoCS, a survey targetting the Fornax Cluster, the second closest galaxy cluster, with a similar observing strategy as HeViCS, was presented.

The HELGA survey, covering a relatively large area around the closest massive galaxy, including the Andromeda Galaxy M31 itself, was introduced in Chapter 5, along with its first results of SED fits determined dust masses and temperatures for a set of concentric elliptical apertures centred on the bulge of the galaxy.

The HEROES project, started off with *Herschel* observations of seven large edge-on spiral galaxies, was introduced in Chapter 6, describing the morphology and investigating the radial and vertical profiles of the dust FIR emission in the galaxies of the sample. The double-exponential dust mass density distribution often used in the literature generally provides a decent model for this FIR emission, notwithstanding some local peaks and variations, likely associated with spiral arms, rings, star formation complexes, or, in two instances, an AGN in the bulge. Dust masses calculated from radiative transfer fits to optical extinction in the literature were compared to those derived from SED fits to the global *Herschel* fluxes. This comparison confirmed earlier studies which used lower resolution FIR data, showing the same discrepancy between optically and FIR determined dust masses, with the latter being up to a few times higher than the former.

These achievements give rise to further investigations, some of which are described in the next overview of the possible future research.

Although the current implementation within SKIRT of the dust emission by the hot VSGs and PAHs already does a very decent job, the use of a library approach is still a bit too coarse for certain modelling applications, e.g. when the dust size distribution and chemical composition varies with the location within the system. Because running the full DustEM code for each SKIRT dust grid cell individually would prove painstakingly slow at present, this code should be extensively parallelised, for instance applying the ISRF for a particular grid cell to all dust species within that cell concurrently using general purpose GPU functionality.

Since it can be foreseen that the runtime of a general SKIRT simulation will still be quite long after this optimisation, a shift from the current regular grids towards Voronoi grids will be necessary. The reason is that the latter grids can tessellate the space of the simulated system using the least number of grid cells possible under a given resolution condition. These grids are also useful as similar grids are being used in recent astrophysical hydrodynamics codes (e.g. AREPO, Springel 2010), and can therefore be applied to easily read in the results from these simulations and generate images based on them using radiative transfer, which can then be interpreted further.

An application of this more accurate SKIRT version is the study of star formation tracers based on MIR emission, and more specifically the influence of older stellar populations on them. As was shown in this thesis, VSGs and PAHs are predominantly heated

by UV photons, mostly originating from very young stars. However, older stars can also contribute considerably to this heating, even though their radiation field is much softer and consists mainly of optical photons. It can therefore be the case that a significant amount of the dust MIR emission is not related to very young stars and thus to star formation. This constitutes a very problematic situation for widely used SFR tracers, such as the $24\ \mu\text{m}$ continuum, the $8\ \mu\text{m}$ PAH band emission and the total integrated $8\text{--}1000\ \mu\text{m}$ IR (TIR) emission (Kennicutt 1998; Calzetti et al. 2010), which all cover at least part of the MIR spectrum. Using both analytical toy models and results from smoothed particle hydrodynamics (SPH) simulations, SKIRT can be used to calculate the relative contribution of the old stellar population to the MIR dust emission for various types of galaxies along the Hubble sequence. The resulting influence on the SFR tracers can then be applied to real galaxy data and compared with other SFR correlating quantities, such as the ionised gas, total dust mass, total gas mass, and the CO intensity (see e.g. Eales et al. 2012).

The HeViCS and HeFoCS *Herschel* observations have been concluded and the first scientific results have been published, mostly using only single cross-scan data. The scientific exploitation which still lies ahead includes the cold dust in the extreme outskirts of galaxies and the intra-cluster medium. For both it was known from the onset that they would require the full dataset, but for the latter it is not even certain that the intended goals can be achieved, given the intrinsic difficulties involved in the subtraction of the foreground cirrus.

The other scientific goals of these programmes have been handled for HeViCS, but not all using the full coverage, so the intermediate results can be confirmed or refuted using the complete dataset. Many of these goals still have to be investigated for the HeFoCS data, and their results compared with those found in the HeViCS data. In particular the modelling of the entire UV to sub-mm SEDs of the galaxies in the fields, and the study of quantities derived from it, such as star formation rates, will greatly benefit from the addition of WISE (MIR) and JCMT (sub-mm) data, as well as CO molecular gas observations. In the mid-term future, upcoming space-based observatories and instruments such as SPICA/SAFARI (FIR) and JWST (NIR/MIR), will no doubt turn out to be extremely valuable towards achieving the planned goals of these programmes, e.g. providing high-resolution spectroscopic observations.

The HEROES investigation has laid the foundations for an extensive study of the spatial distribution, amount and properties of the different components within the ISM, of the stars and of the dark matter in a statistical sample of edge-on galaxies. Spatially resolved pixel-by-pixel SED fitting and construction of state-of-the-art radiative transfer models for these galaxies over the whole UV/optical/IR/sub-mm range using SKIRT and FitSKIRT (De Geyter et al. 2013) will culminate in a comparison between simu-

lated images and *Herschel* maps. This will allow us to tackle the dust energy balance problem and put strong quantitative constraints on, or possibly discriminate between, the various explanations for this discrepancy.

It should be mentioned that the investigation of the *HEROES* galaxies discussed in Chapter 6 starts from an axisymmetric, 2D double-exponential model for the dust distribution, whereas this analytical approach is obviously an oversimplified representation of the real situation, which is naturally 3D and contains features such as spiral arms, rings, star formation regions and other clumps which break the symmetry of the system. In our group we are currently approaching this problem along two different roads. A first one is an extension of the FitSKIRT code to fit observations with 3D models (in a similar fashion to the discussion in Schechtman-Rook et al. 2012a,b), working on NGC 891 (De Geyter et al., in preparation) and M51 (De Looze et al., in preparation). The second path we are following could be considered as working in the other direction, by running the SKIRT code on the results from hydrodynamical (SPH and grid-based hydro) simulations. By fitting simulations of dust-affected edge-on spiral galaxies with FitSKIRT, thereby doing the same as with real data, we will be able to investigate the effect our simplified model assumptions have on the end result (Camps et al., in preparation).

Situering van het onderzoeksgebied

De rol van stof in het interstellair medium

Het interstellair stof speelt een belangrijke rol in het interstellair medium (ISM) waarmee sterrenstelsels doordrongen zijn, ook al maakt het slechts 1% uit van de totale massa aan stof en gas in dit mengsel. Deze stofkorreltjes bestaan vooral uit koolstof en silicaten en zijn vaak (veel) kleiner dan 1 micrometer. Ondanks hun kleine aandeel in de massa staan ze mee in voor de fysische en chemische processen die aan de basis liggen van de vorming van sterren en planeten. Zelf worden ze dan weer vooral gevormd bij het levenseinde van een ster, wanneer die steeds meer materiaal, vooral metalen¹, uitstoot in de sterrenwind of gewoon wegslingert in de (super- of rode) reusfase, of bij de supernova-ontploffing als het een voldoende zware ster betreft. Deze metalen koelen af in de interstellaire ruimte, klonteren steeds meer samen en beginnen dus op die manier stof te vormen.

Bij de vorming van sterren in moleculaire gaswolken, zorgt het interstellair stof voor voldoende afscherming tegen de intense ultraviolette straling afkomstig van nabije zware sterren opdat delen van deze wolken kunnen samentrekken om uiteindelijk in nieuwe sterren omgezet te worden. Het oppervlak van stofkorrels biedt ook plaatsen waar atomair in moleculair waterstof kan omgezet worden en treedt op die manier als katalysator op. Er kunnen op die manier echter ook veel complexere moleculen gevormd worden.

Tot zo'n halve eeuw geleden vond men de absorberende en verstrooiende invloed van stof hinderlijk, omdat het spectrum van achterliggende bronnen erdoor wordt 'aangetaast' (vooral dan de kortere golflengten, waardoor de bron roodverkleurd lijkt). In de laatste decennia is men het stof zelf beginnen bestuderen. Door namelijk het spectrum van zo'n verkleurde bron naast dat van een vergelijkbare, niet verkleurde bron te leggen, kan men een attenuatie- of extinctiecurve opstellen die de 'uitdoving' van het licht

¹ In de sterrenkunde worden alle elementen zwaarder dan helium als 'metalen' aangeduid.

in functie van de golflengte toont. Daaruit kan men dan bepaalde eigenschappen van het stof, zoals de samenstelling, afleiden.

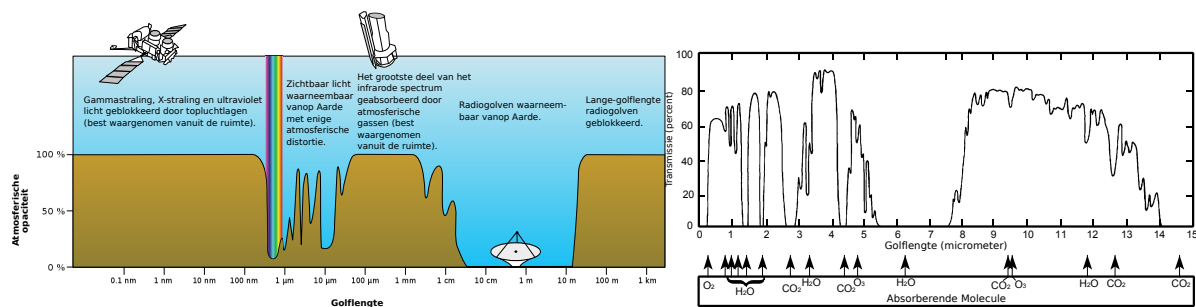
Het stof straalt ook zelf licht uit, maar bijna uitsluitend in het infrarood of zelfs langere golflengten. Hoewel er een enorme variatie is in samenstelling en grootte van de stofdeeltjes, blijkt toch dat het spectrum van een gewijzigde zwarte straler met slechts één effectieve temperatuur en spectrale index in vele gevallen volstaat om de (ver-)infraroodemissie van deze stofdeeltjes te fitten. Een belangrijke factor hierin is dat de meeste massa van het stof zit opgeslagen in zogenaamde 'grote' stofdeeltjes (typisch 0.1 tot ongeveer 1 micrometer), en die blijken zich effectief ook als een gewijzigde zwarte straler te gedragen omdat ze in lokaal thermisch evenwicht zijn met het interstellaire stralingsveld (afgekort tot ISRF in het Engels).

Deze grote stofdeeltjes kunnen echter niet de hoge temperaturen bereiken die nodig zijn om het mid-infrarood gedeelte van het spectrum te verklaren. Daarvoor staan (erg) kleine stofdeeltjes (kleiner dan 10 nanometer) in, die geen lokaal thermisch evenwicht kunnen bereiken, omdat ze slechts sporadisch fotonen absorberen, maar dan wel enorm verhit worden en vervolgens geleidelijk weer afkoelen. Het nabije- en mid-infrarode spectrum bevat echter ook een aantal vrij smalle, heldere pieken, die meer dan waarschijnlijk verklaard kunnen worden door polycyclische aromatische koolwaterstoffen (afgekort tot PAHs in het Engels of PAK's in het Nederlands), eigenlijk grote moleculen, die evenmin in lokaal thermisch evenwicht zijn, maar stralen bij een aantal energieniveaus.

Modellering van stralingsoverdracht

Een belangrijke onderzoeksmethode om de fysische en chemische eigenschappen van interstellair stof te bestuderen, verloopt via modellering van de stralingsoverdracht, waarbij de interactie tussen straling, afkomstig van lichtbronnen, en materie wordt nagegaan. De stralingsoverdrachtsvergelijking bevat zowel bron- als afvoertermen en beschrijft de intensiteit van een stralingsveld op een bepaalde plaats bij een specifieke golflengte en in een bepaalde richting. De brontermen bestaan uit de verschillende soorten straling (zowel afkomstig van sterren als van het stof), terwijl de afvoertermen worden gevormd door absorptie en verstrooiing. Dit laatste proces vormt echter ook een bronterm voor alle andere richtingen. Bij het oplossen van deze vergelijking moet echter steeds aan de energiebalans voldaan worden, zodat de totale energie door het stof geabsorbeerd over het hele spectrum ook weer helemaal moet uitgestraald worden door dat stof.

Deze modellering is echter een bijzonder complex probleem, omdat het 3 ruimtelijke dimensies, 2 richtingsdimensies en een golflengtedimensie bevat (en dan nog enkel



Figuur 8.1: Atmosferische opaciteit doorheen het elektromagnetische spectrum (*links*) en de transmissie in een deel van het infrarood, met aanduiding van een aantal absorberende moleculen (*rechts*). Afbeeldingen: NASA/Wikimedia Commons & *Electronic Warfare and Radar Systems Engineering Handbook*.

wanneer verondersteld wordt dat geen verandering in de tijd optreedt), en bovendien gedraagt de vergelijking zich niet-lokaal en niet-lineair. Analytische oplossingen zijn daarom nagenoeg onmogelijk, behalve in enkele zeer speciale gevallen. Bijgevolg moet men zijn toevlucht nemen tot bv. Monte Carlo benaderingen, waarbij men door willekeurige getallen laat bepalen hoe een zeer groot aantal fotonen zich door het systeem propageert en beïnvloed wordt door het stof. Hierdoor kan men vrij nauwkeurig een realistisch systeem simuleren.

De emissie afkomstig van de grote stofdeeltjes is relatief eenvoudig te bepalen, net omdat ze in lokaal thermisch evenwicht zijn met het stralingsveld, maar dit is niet langer het geval voor de kleine stofkorrels. Deze vereisen een speciale wiskundige behandeling, waarbij de temperatuurverdeling van de verschillende deeltjes moet berekend worden, iets wat een pak complexer is dan wat nodig is voor de grote deeltjes.

Infraroodastronomie: stof in sterrenstelsels

Hoewel William Herschel al in 1800 zijn ontdekking van het infrarood gedeelte van het spectrum van de Zon rapporteerde, is infraroodastronomie pas in de tweede helft van vorige eeuw echt tot bloei gekomen, enerzijds vanwege de sterke technologische ontwikkeling van de nodige detectoren, en anderzijds door het ontstaan van de ruimtevaart. Dat laatste is een vereiste voor infraroodastronomie, omdat slechts een beperkt deel van het infraroodspectrum helemaal doorheen de atmosfeer kan dringen, o.a. vanwege de waterdamp in de lucht (zie Figuur 8.1).

Er moet een onderscheid gemaakt worden tussen nabije-infrarood- (NIR) enerzijds en mid-/ver-infrarood (MIR/FIR) astronomie anderzijds, zowel qua lichtbronnen als wat betreft detectortechnologie. Het eerste is voornamelijk afkomstig van stellaire emissie, terwijl MIR- en FIR-straling vooral veroorzaakt wordt door warme tot koude stofdeeltjes. Voor NIR-straling kan men gebruik maken van dezelfde CCD-technologie die

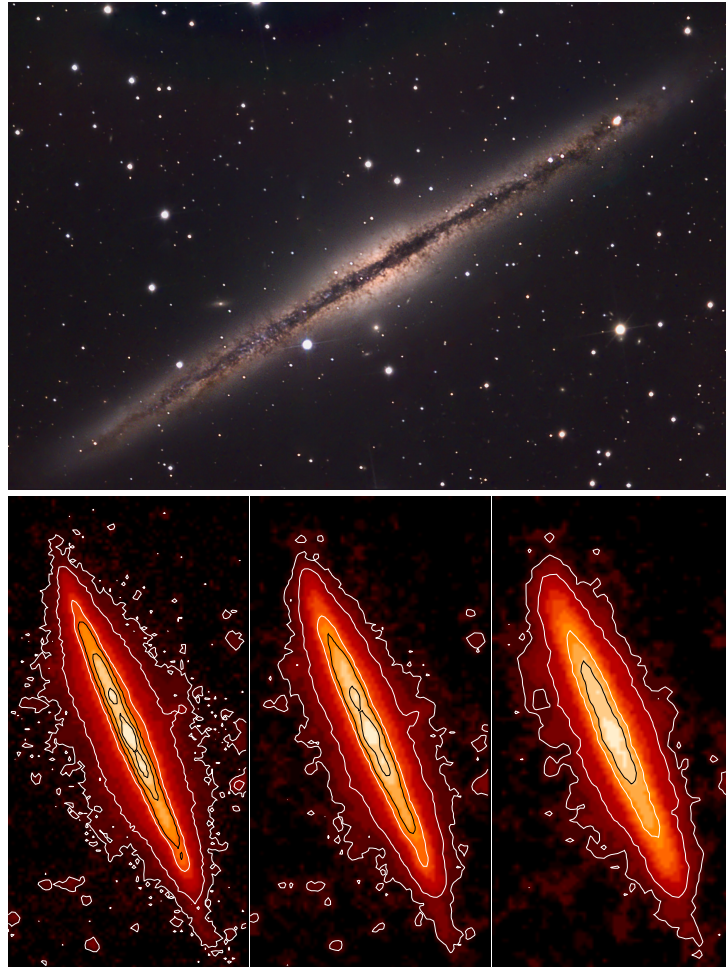
ook in de optische sterrenkunde zijn toepassing vindt, maar MIR- en FIR-emissie kan hiermee doorgaans niet meer efficiënt opgevangen worden. Hiervoor zoekt men dan zijn toevlucht tot andere technologieën, zoals bv. bolometers, die echter vaak tot (zeer) lage temperaturen gekoeld moeten worden. Daarom hebben IR ruimte-observatoria meestal een missieduur die beperkt is in de tijd door de hoeveelheid koelmiddel aan boord.

Een bijkomende moeilijkheid is de diffractielimiet, die bepaalt dat om hetzelfde onderscheidend vermogen te bereiken maar bij langere golflengte, men een licht-opvangend objectief moet gebruik dat evenredig toeneemt in diameter. Omdat men ook beperkt is in de dimensies van een telescoop die in de ruimte kan gebracht worden, neemt de resolutie dus meestal af naarmate men verder in het infrarood wil waarnemen. Wat dat betreft is op dit moment het *Herschel Space Observatory* het summum, met een diameter van 3.5 m voor de hoofdspiegel en een FIR/submillimeter bereik van 55 tot 671 μm .

Herschel vormt dan ook het ideale instrument om de eigenschappen en verdeling van het koude interstellaire stof, dat dit deel van het spectrum domineert, te bestuderen, met name in nabije sterrenstelsels. Hieruit kan dan belangrijke informatie achterhaald worden, o.a. omtrent stervorming en dus ook de evolutiegeschiedenis van sterrenstelsels. In deze vormen edge-on spiraalgalaxieën — sterrenstelsels waarvan de schijf met de rand naar ons georiënteerd is — een bijzonder nuttig onderzoeksobject. Alle licht afkomstig uit dit stelsel is namelijk door de projectie geconcentreerd in een smalle strook aan de hemel, en de oppervlaktehelderheid ligt een stuk hoger dan wanneer hetzelfde systeem loodrecht op het vlak van de schijf aanschouwd zou worden. Als gevolg daarvan springt op optische opnames het stof vaak in het oog als een dichte of net diffuse streep die de centrale as van de geprojecteerde schijf volgt. De extinctie én emissie door het stof kunnen daardoor tot grote afstanden van het centrum waargenomen worden, zowel binnen het vlak van de sterrenschijf als in de verticale richting, loodrecht op dit vlak (Figuur 8.2).

Veruit de striktste randvoorwaarden aan eigenschappen en verdeling van stof in spiraalstelsels worden opgelegd door een zelf-consistente behandeling van extinctie en thermische emissie door het stof en de bijhorende studie van de energiebalans. Door realistische modellen van stralingsoverdracht te fitten aan optische beelden van edge-on sterrenstelsels, heeft men hun stofverdeling vrij goed kunnen schatten, waaruit blijkt dat de stofschijf zelf dunner, maar radiaal uitgestrekter is dan de schijf gevormd door alle sterren in het spiraalstelsel.

In het algemeen blijkt echter dat in spiraalgalaxieën gemiddeld zo'n 30% van het sterrenlicht wordt geabsorbeerd door het stof en vervolgens weer uitgestraald als thermi-



Figuur 8.2: Een edge-on galaxie, NGC 891, in kleurencomposiet (*boven*) en zoals waargenomen door *Herschel*/SPIRE (*onder*) rond de golflengten (van links naar rechts) 250, 350 en 500 μm . Afbeeldingen: Dale Cupp/Flynn Haase/NOAO/AURA/NSF & Bianchi & Xilouris (2011).

sche FIR/sub-mm emissie, terwijl de modellen slechts zo'n 10% absorptie bereiken. Dit is bijzonder merkwaardig voor edge-on sterrenstelsels, omdat de modellen van de stralingsoverdracht wel degelijk de optische extinctie correct verklaren, maar voor de FIR/sub-mm emissie waarden voorspellen die slechts een derde bedragen van wat wordt waargenomen. Een meer gedetailleerde studie van deze stelsels, gebruik makend van zowel modellen als FIR/sub-mm waarnemingen, kunnen meer duidelijkheid scheppen over een aantal van de voorgestelde verklaringen voor dit raadsel.

Stralingsoverdracht en thermische emissie door kleine stofdeeltjes

SKIRT is een Monte Carlo simulatieprogramma ontwikkeld aan de UGent voor de studie van stralingsoverdracht in driedimensionale modellen, om de eigenschappen van het stof in sterrenstelsels te onderzoeken. Een belangrijk onderdeel dat nog ontbrak, was de zelf-consistente berekening van de thermische emissie door de kleinste stof-

deeltjes en PAK's. De code die we speciaal geschreven hebben om hieraan te verhelpen, lijkt de temperatuurverdeling van de stofdeeltjes correct te berekenen in vergelijking met wat in de literatuur te vinden is, maar blijkt nog kinderziekten te vertonen bij de behandeling van complexere, realistische mengsels van verschillende soorten stofdeeltjes.

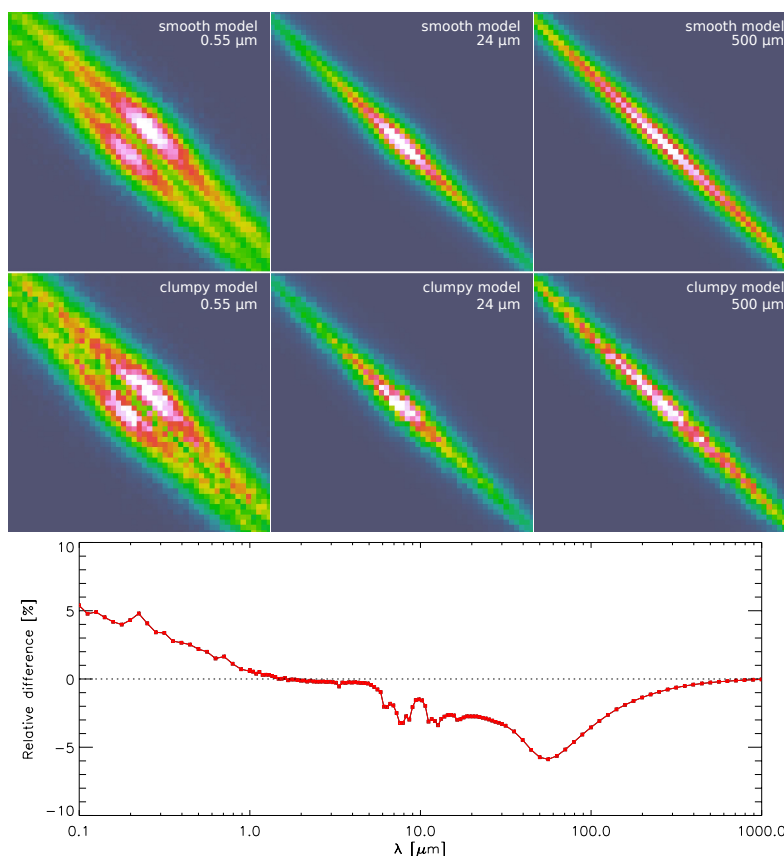
Omdat ook de snelheid van deze code nog onvoldoende is om voluit gebruikt te worden in 3D simulaties, hebben we in plaats daarvan gebruik gemaakt van een extern programma, DustEM, en een speciale aanpak gebaseerd op een bibliotheek. Hierbij wordt een representatief staal genomen van de verschillende mogelijke stralingsvelden die doorheen het gesimuleerde model optreden en vervolgens aan de hand van 2 parameters geïndexeerd in een tweedimensionale parameter ruimte. Voor dit staal wordt door DustEM dan de thermische emissie door stofdeeltjes berekend, en in elke cel van de globale simulatie wordt dan de thermische emissie gebruikt van het stralingsveld uit de bibliotheek die het best overeenstemt met het veld in die cel. Op die manier hebben we kunnen demonstreren dat het mogelijk is om efficiënte en nauwkeurige Monte Carlo simulaties van stralingsoverdracht uit te voeren voor willekeurige driedimensionale structuren bestaande uit miljoenen cellen, met inbegrip van een volledige berekening van de emissie door de kleinste stofdeeltjes (Figuur 8.3). Hierdoor wordt het aantal toepassingen voor dit soort simulaties enorm uitgebreid.

Ver-infrarood observaties van nabije sterrenstelsels

Zoals eerder vermeld, kunnen we ook veel leren over de eigenschappen van interstellair stof door het niet alleen in extinctie/attenuatie, maar ook in emissie waar te nemen. Omdat dit stof doorgaans erg koud is (~ 20 K) en daardoor bijna uitsluitend in het ver-infrarood straalt, vergt deze observaties speciale instrumenten. Gebruik makend van de in 2009 gelanceerde *Herschel Space Observatory*, hebben we bijgedragen aan een aantal grote waarnemingsprojecten voor de studie van dit stof in nabije sterrenstelsels; voor sommige van deze programma's hebben we zelfs de leiding in handen.

Dataverwerking van *Herschel* waarnemingen

Omdat de data afkomstig van *Herschel* eerst nog verwerkt moet worden om de ruwe gegevens om te zetten in beelden die geïnterpreteerd kunnen worden, hebben we ons in eerste instantie toegelegd op een studie van de verschillende stappen van de algemene standaard pijplijn die hiervoor instaat voor het PACS instrument. We hebben hierin vervolgens een aantal aanpassingen aangebracht die van nut zijn voor onze specifieke data. Daarnaast hebben we ook enkele algoritmes onderzocht die instaan voor

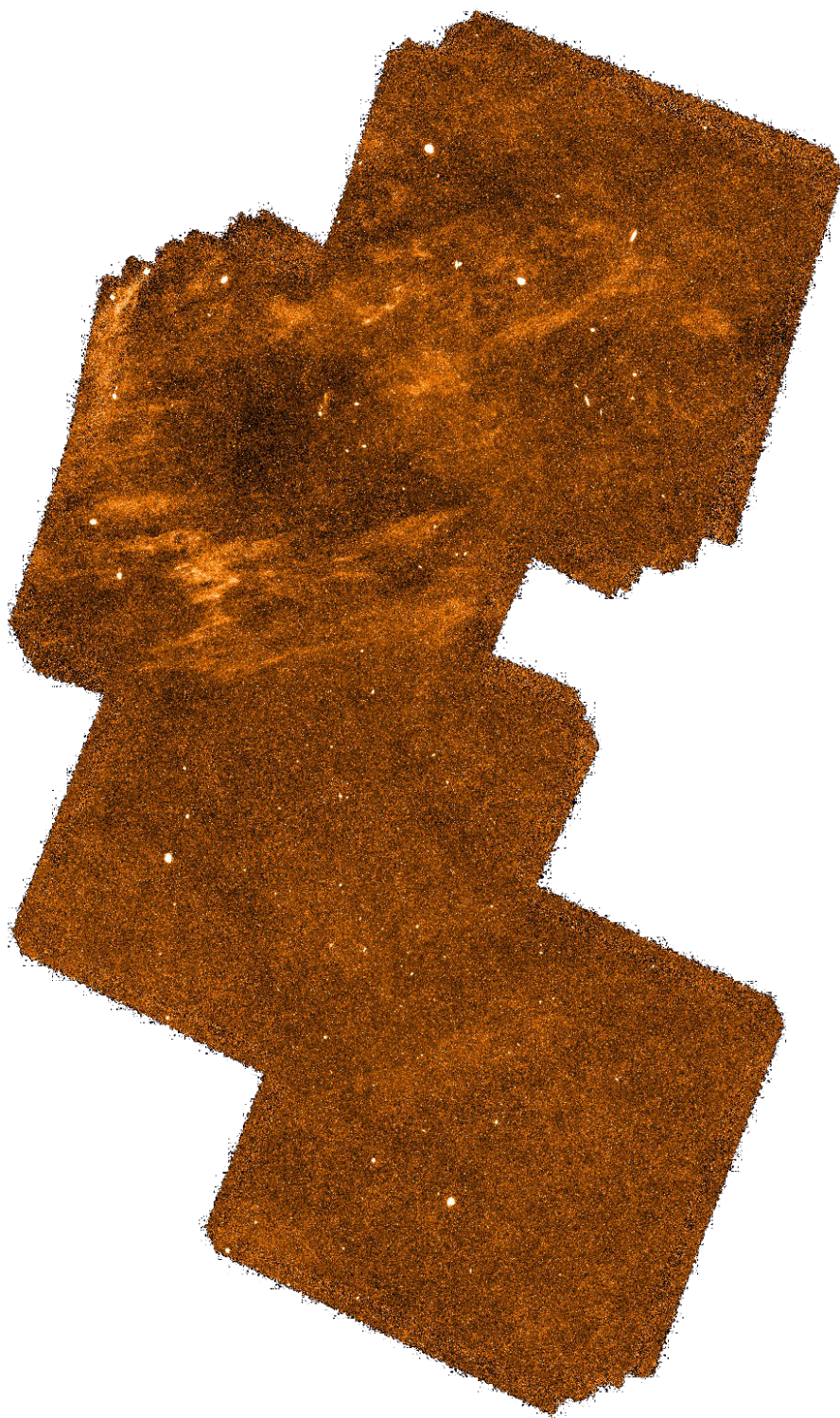


Figuur 8.3: *Boven:* Een vergelijking tussen een effen (bovenste rij) en een klonterige (onderste rij) stofverdeling in een 3D model van UGC 4754, met beelden voor verschillende golflengten. *Onder:* Het relatieve verschil tussen de SED's van de modellen met een klonterige en een effen stofverdeling.

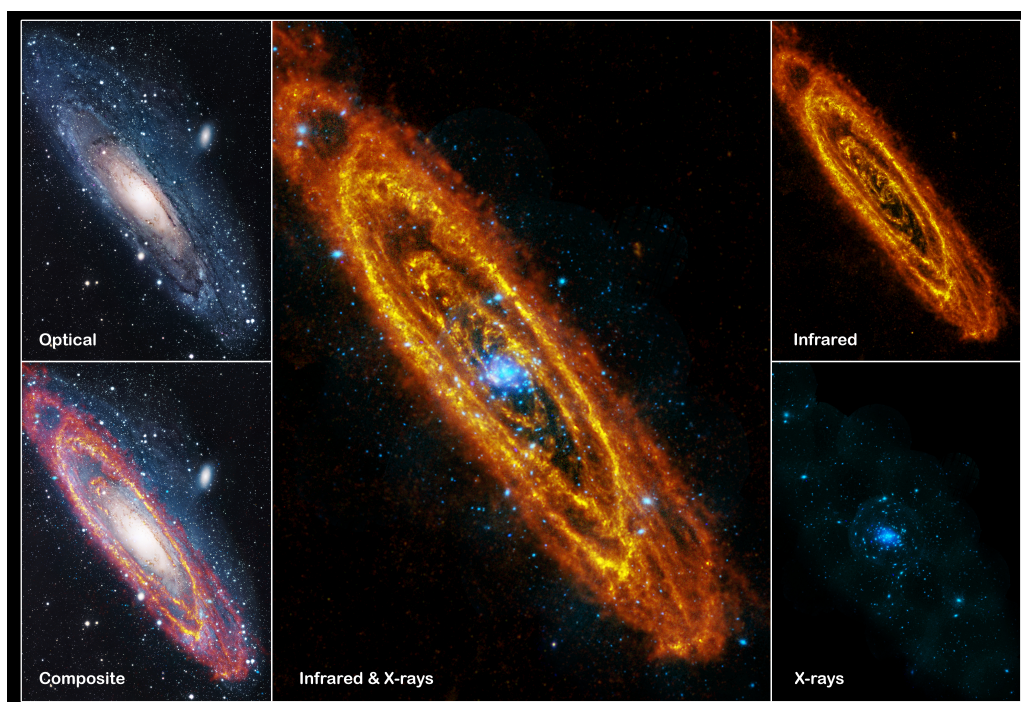
de finale omzetting in beelden en kritisch geëvalueerd welke het best toegepast worden in onze projecten. Door de grote omvang van de data die verwerkt moet worden door zowel de standaard pijplijn als deze algoritmes, vergde dit onderzoek erg veel tijd. Ook nu nog is deze beeldvorming een erg langdurig werk, dat vooral afhangt van de grootte van de waarnemingen.

De *Herschel* Virgo Cluster Survey (HeViCS)

De opgedane kennis over de dataverwerking hebben we toegepast in een aantal waarnemingsprogramma's, die allemaal tot doel hebben nabije sterrenstelsels en clusters te observeren, en meer specifiek het interstellair stof dat deze objecten bevatten. Voor een studie van de eigenschappen van het stof op verschillende locaties in de Virgo Cluster (Figuur 8.4), de dichtstbijzijnde massale groepering van sterrenstelsels, hebben we dus de PACS data verwerkt. Een aantal resultaten werden besproken, zoals het feit dat de ver-infraroodstraling afkomstig van M87, een massief elliptisch ster-



Figuur 8.4: De Virgo Cluster zoals waargenomen met *Herschel*/SPIRE 250 μm . De uiterste afmetingen bedragen ongeveer $15^\circ \times 9^\circ$.

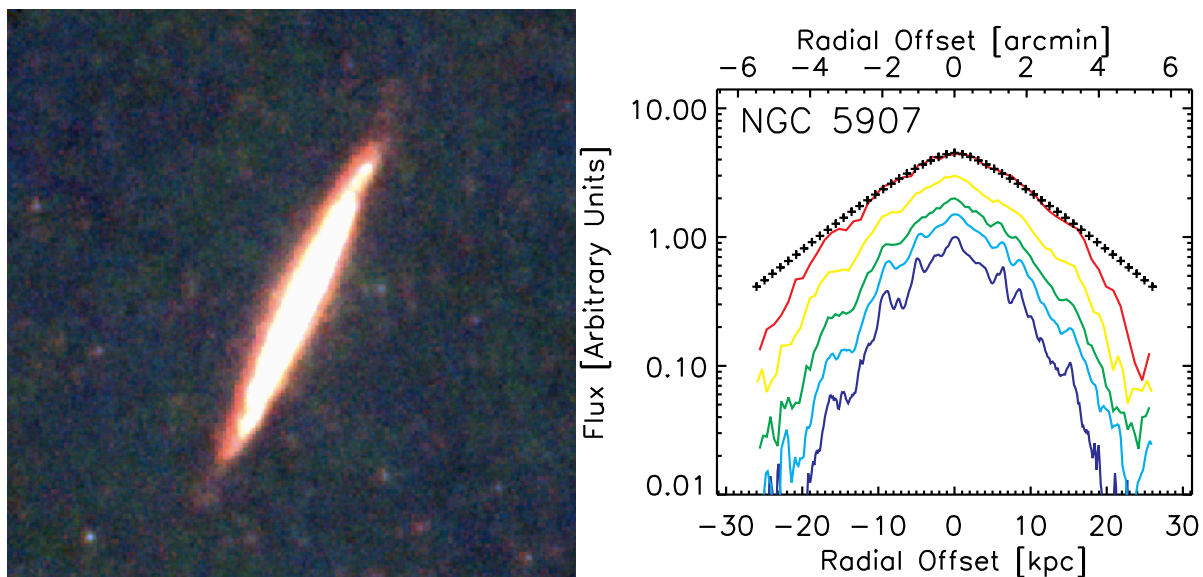


Figuur 8.5: De Andromedanevel, of M31, waargenomen in het optische deel van het spectrum (linksboven), in het ver-infrarood met *Herschel* (rechtsboven), en in X-straling met *XMM-Newton* (rechtsonder). Centraal zijn de laatste twee samengesteld, en linksonder alle drie. Afbeeldingen: ESA/*Herschel*/PACS/SPIRE/J. Fritz, UGent; ESA/*XMM-Newton*/EPIC/W. Pietsch, MPE; R. Gendler

renstelsel in het centrum van de Virgo Cluster, nagenoeg volledig te verklaren is door synchrotronstraling, veroorzaakt door de versnelling van geladen deeltjes, en geen bijkomend koud stof vereist. De massa en temperatuur van het stof werd bepaald in een aantal spiraal- en stervormende dwergsterrenstelsels. Dit gebeurde door middel van het fitten aan de *Herschel* datapunten van de spectrale energiedistributie (SED), die de verdeling volgens golflengte van de uitgestraalde energie geeft, van een gewijzigde zwarte straler. Voor een selectie van sterrenstelsels die helder stralen in het ver-infrarood werd de verdeling volgens lichtkracht bepaald, net als hun stofmassa's en -temperaturen. En hoewel dit onderzoek dus vooral gericht is op extragalactisch stof, werden toch een aantal planetoïden, die door het beeldveld schoven tijdens de opnames, gedetecteerd en geïdentificeerd. Daarnaast werd een vervolgproject, de *Herschel* Fornax Cluster Survey (HeFoCS), voorgesteld, dat gelijkaardig onderzoek beoogt, maar dan van de Fornax Cluster, de op één na dichtste cluster.

De *Herschel* Exploitation of Local Galaxy Andromeda (HELGA)

Met het HELGA project hebben we de ruime omgeving van Andromedanevel M31, het dichtstbijzijnde grote sterrenstelsel, waargenomen in het ver-infrarood op een schaal



Figuur 8.6: *Links:* Een valse-kleurencomposiet bestaande uit PACS 100 (blauw), PACS 160 (groen) en SPIRE 250 μm (rood) voor *HEROES* spiraalstelsel NGC 5907. *Rechts:* De radiale profielen van de ver-infrarood emissie voor NGC 5907. De *Herschel* data zijn als volgt aangeduid: PACS 100 (blauw), PACS 160 (cyaan), SPIRE 250 (groen), SPIRE 350 (geel) en SPIRE 500 μm (rood). De zwarte kruisjes duiden het dubbel-exponentiële model aan.

zonder voorgaande (Figuur 8.5). Met behulp van deze opnamen hebben we de massa en temperatuur van het stof in verschillende regio's van dit sterrenstelsel bepaald aan de hand van SED fits, en hebben we een diepgaande studie van het interstellair medium in het satellietstelsel M 110 (NGC 205) kunnen uitvoeren.

***HERschel* Observations of Edge-on Spirals (*HEROES*)**

Een laatste belangrijk *Herschel* project dat in dit werk behandeld werd, is een studie van 7 grote edge-on spiraalstelsels, met als algemeen doel het verband tussen de eigenschappen, hoeveelheid en verdeling van de verschillende componenten van het interstellair medium, de sterren en de donkere materie in deze sterrenstelsels te onderzoeken. Het is o.a. de bedoeling om de waarnemingen te analyseren en interpreteren aan de hand van SKIRT simulaties.

Hierbij zijn de *Herschel* observaties van cruciaal belang, omdat daar de verdeling van het koude interstellair stof mee kan bepaald worden. We hebben daarom de vorm en de radiale en verticale profielen van de ver-infrarood emissie beschreven voor deze stelsels (Figuur 8.6). Het blijkt dat het dubbel-exponentiële model dat vaak in de literatuur gebruikt wordt voor de massaverdeling van het stof, ook de ver-infrarood emissie goed beschrijft, enkele lokale variaties niet te na gesproken. Deze laatste hangen meer dan waarschijnlijk samen met de spiraalarmen, ringstructuren, stervormingsgebieden,

of een actieve kern in het centrum van het stelsel.

Opnieuw hebben we door fitten aan de *Herschel* datapunten de stoftemperatuur en stofmassa bepaald voor de verschillende stelsels. Deze massa's, berekend aan de hand van de ver-infrarood emissie, bleken tot enkele malen groter te zijn dan wat eerder kon afgeleid worden uit de optische extinctie en bijhorende simulaties van de stralings-overdracht, een discrepantie die vroeger ook al opgemerkt werd, gebruik makend van ver-infrarood data met lagere resoluties.

Bibliography

- Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1985, *ApJ*, 290, L25
- Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, *ApJS*, 71, 733
- Alton, P. B., Bianchi, S., Rand, R. J., et al. 1998a, *ApJ*, 507, L125
- Alton, P. B., Rand, R. J., Xilouris, E. M., et al. 2000a, *A&AS*, 145, 83
- Alton, P. B., Trewhella, M., Davies, J. I., et al. 1998b, *A&A*, 335, 807
- Alton, P. B., Xilouris, E. M., Bianchi, S., Davies, J., & Kylafis, N. 2000b, *A&A*, 356, 795
- Alton, P. B., Xilouris, E. M., Misiriotis, A., Dasyra, K. M., & Dumke, M. 2004, *A&A*, 425, 109
- Andonov, A., Arbuzov, A. B., Bondarenko, S. G., et al. 2010, *Physics of Atomic Nuclei*, 73, 1761
- Aniano, G., Draine, B. T., Calzetti, D., et al. 2012, *ApJ*, 756, 138
- Aniano, G., Draine, B. T., Gordon, K. D., & Sandstrom, K. 2011, *PASP*, 123, 1218
- Auld, R., Bianchi, S., Smith, M. W. L., et al. 2013, *MNRAS*, 428, 1880
- Baes, M. 2008, *MNRAS*, 391, 617
- Baes, M., Clemens, M., Xilouris, E. M., et al. 2010a, *A&A*, 518, L53
- Baes, M., Davies, J. I., Dejonghe, H., et al. 2003, *MNRAS*, 343, 1081
- Baes, M. & Dejonghe, H. 2001a, *ApJ*, 563, L19
- Baes, M. & Dejonghe, H. 2001b, *MNRAS*, 326, 733
- Baes, M. & Dejonghe, H. 2002, *MNRAS*, 335, 441

- Baes, M., Dejonghe, H., & Davies, J. I. 2005a, in American Institute of Physics Conference Series, Vol. 761, The Spectral Energy Distributions of Gas-Rich Galaxies: Confronting Models with Data, ed. C. C. Popescu & R. J. Tuffs, 27–38
- Baes, M., Fritz, J., Gadotti, D. A., et al. 2010b, *A&A*, 518, L39
- Baes, M., Stamatellos, D., Davies, J. I., et al. 2005b, *New A*, 10, 523
- Baes, M., Verstackpen, J., De Looze, I., et al. 2011, *ApJS*, 196, 22
- Bajaja, E. & Gergely, T. E. 1977, *A&A*, 61, 229
- Barmby, P., Ashby, M. L. N., Bianchi, L., et al. 2006, *ApJ*, 650, L45
- Barnaby, D. & Thronson, Jr., H. A. 1992, *AJ*, 103, 41
- Bendo, G. J., Boselli, A., Dariush, A., et al. 2012a, *MNRAS*, 419, 1833
- Bendo, G. J., Galliano, F., & Madden, S. C. 2012b, *MNRAS*, 423, 197
- Bendo, G. J., Galliano, F., & Madden, S. C. 2012c, *VizieR Online Data Catalog*, 742, 30197
- Bendo, G. J., Wilson, C. D., Pohlen, M., et al. 2010a, *A&A*, 518, L65
- Bendo, G. J., Wilson, C. D., Warren, B. E., et al. 2010b, *MNRAS*, 402, 1409
- Bertin, E. & Arnouts, S. 1996, *A&AS*, 117, 393
- Bertola, F., Bressan, A., Burstein, D., et al. 1995, *ApJ*, 438, 680
- Bianchi, S. 2007, *A&A*, 471, 765
- Bianchi, S. 2008, *A&A*, 490, 461
- Bianchi, S., Davies, J. I., & Alton, P. B. 2000a, *A&A*, 359, 65
- Bianchi, S., Ferrara, A., Davies, J. I., & Alton, P. B. 2000b, *MNRAS*, 311, 601
- Bianchi, S., Ferrara, A., & Giovanardi, C. 1996, *ApJ*, 465, 127
- Bianchi, S. & Xilouris, E. M. 2011, *A&A*, 531, L11
- Bicay, M. D. & Giovanelli, R. 1987, *ApJ*, 321, 645
- Billot, N., Sauvage, M., Rodriguez, L., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7741, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V, ed. W. S. Holland & J. Zmuidzinas

- Binggeli, B., Sandage, A., & Tammann, G. A. 1985, *AJ*, 90, 1681
- Binggeli, B., Tammann, G. A., & Sandage, A. 1987, *AJ*, 94, 251
- Biretta, J. A., Stern, C. P., & Harris, D. E. 1991, *AJ*, 101, 1632
- Bland-Hawthorn, J., Ekers, R. D., van Breugel, W., Koekemoer, A., & Taylor, K. 1995, *ApJ*, 447, L77
- Block, D. L., Bournaud, F., Combes, F., et al. 2006, *Nature*, 443, 832
- Böhringer, H., Belsole, E., Kennea, J., et al. 2001, *A&A*, 365, L181
- Boquien, M., Buat, V., Boselli, A., et al. 2012, *A&A*, 539, A145
- Boselli, A., Boissier, S., Cortese, L., et al. 2009, *ApJ*, 706, 1527
- Boselli, A., Ciesla, L., Buat, V., et al. 2010a, *A&A*, 518, L61
- Boselli, A., Ciesla, L., Cortese, L., et al. 2012, *A&A*, 540, A54
- Boselli, A., Eales, S., Cortese, L., et al. 2010b, *PASP*, 122, 261
- Boselli, A. & Gavazzi, G. 2006, *PASP*, 118, 517
- Bottema, R. 1995, *A&A*, 295, 605
- Bottema, R. 1996, *A&A*, 306, 345
- Bottema, R., Shostak, G. S., & van der Kruit, P. C. 1987, *Nature*, 328, 401
- Braun, R. 2012, *ApJ*, 749, 87
- Braun, R., Thilker, D. A., Walterbos, R. A. M., & Corbelli, E. 2009, *ApJ*, 695, 937
- Bruzual, G., Magris, G., & Calvet, N. 1988, *ApJ*, 333, 673
- Buson, L., Bressan, A., Panuzzo, P., et al. 2009, *ApJ*, 705, 356
- Byun, Y. I., Freeman, K. C., & Kylafis, N. D. 1994, *ApJ*, 432, 114
- Calzetti, D. 2011, in *EAS Publications Series*, Vol. 46, *PAHs and the Universe: A Symposium to Celebrate the 25th Anniversary of the PAH Hypothesis*, ed. C. Joblin & A. G. G. M. Tielens, 133–141
- Calzetti, D., Kennicutt, R. C., Engelbracht, C. W., et al. 2007, *ApJ*, 666, 870
- Calzetti, D., Wu, S.-Y., Hong, S., et al. 2010, *ApJ*, 714, 1256

- Cantalupo, C. M., Borrill, J. D., Jaffe, A. H., Kisner, T. S., & Stompor, R. 2010, *ApJS*, 187, 212
- Cappellari, M. 2002, *MNRAS*, 333, 400
- Cappellari, M., Bacon, R., Bureau, M., et al. 2006, *MNRAS*, 366, 1126
- Casertano, S., de Mello, D., Dickinson, M., et al. 2000, *AJ*, 120, 2747
- Cashwell, E. D. & Everett, C. J. 1959, *A Practical Manual on the Monte Carlo Method for Random Walk Problems*, Vol. v. 1 (New York: Pergamon Press)
- Chandrasekhar, S. 1960, *Radiative transfer* (Dover Publications Inc.)
- Cheng, E. S., Hill, R. J., MacKenty, J. W., et al. 2000, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4013, *UV, Optical, and IR Space Telescopes and Instruments*, ed. J. B. Breckinridge & P. Jakobsen, 367–373
- Chung, A., van Gorkom, J. H., Kenney, J. D. P., Crawl, H., & Vollmer, B. 2009, *AJ*, 138, 1741
- Clements, D. L., Rigby, E., Maddox, S., et al. 2010, *A&A*, 518, L8
- Comerón, S., Elmegreen, B. G., Knapen, J. H., et al. 2011, *ApJ*, 738, L17
- Compiègne, M. 2010, in *Astronomical Society of the Pacific Conference Series*, Vol. 438, *The Dynamic Interstellar Medium: A Celebration of the Canadian Galactic Plane Survey*, ed. R. Kothes, T. L. Landecker, & A. G. Willis, 55
- Compiègne, M., Verstraete, L., Jones, A., et al. 2011, *A&A*, 525, A103
- Condon, J. J. 1992, *ARA&A*, 30, 575
- Cortese, L., Davies, J. I., Pohlen, M., et al. 2010, *A&A*, 518, L49
- Cotton, W. D., Mason, B. S., Dicker, S. R., et al. 2009, *ApJ*, 701, 1872
- Dalcanton, J. J., Yoachim, P., & Bernstein, R. A. 2004, *ApJ*, 608, 189
- Dale, D. A., Aniano, G., Engelbracht, C. W., et al. 2012, *ApJ*, 745, 95
- Dasyra, K. M., Xilouris, E. M., Misiriotis, A., & Kylafis, N. D. 2005, *A&A*, 437, 447
- Davies, J., Minchin, R., Sabatini, S., et al. 2004, *MNRAS*, 349, 922
- Davies, J. I., Alton, P., Trewhella, M., Evans, R., & Bianchi, S. 1999, *MNRAS*, 304, 495

- Davies, J. I., Auld, R., Burns, L., et al. 2011, MNRAS, 415, 1883
- Davies, J. I., Baes, M., Bendo, G. J., et al. 2010, A&A, 518, L48
- Davies, J. I., Bianchi, S., Baes, M., et al. 2013, MNRAS, 428, 834
- Davies, J. I., Bianchi, S., Cortese, L., et al. 2012, MNRAS, 419, 3505
- De Geyter, G., Baes, M., Fritz, J., & Camps, P. 2013, A&A, 550, A74
- de Grijs, R. & Peletier, R. F. 2000, MNRAS, 313, 800
- de Grijs, R. & van der Kruit, P. C. 1996, A&AS, 117, 19
- De Looze, I., Baes, M., Bendo, G. J., et al. 2012a, MNRAS, 427, 2797
- De Looze, I., Baes, M., Fritz, J., & Verstappen, J. 2012b, MNRAS, 419, 895
- De Looze, I., Baes, M., Parkin, T. J., et al. 2012c, MNRAS, 423, 2359
- De Looze, I., Baes, M., Zibetti, S., et al. 2010, A&A, 518, L54
- De Rijcke, S., Prugniel, P., Simien, F., & Dejonghe, H. 2006, MNRAS, 369, 1321
- de Souza, R. E. & Dos Anjos, S. 1987, A&AS, 70, 465
- de Vaucouleurs, G. 1948, Annales d'Astrophysique, 11, 247
- de Vaucouleurs, G. 1958, ApJ, 128, 465
- Demyk, K. 2011, in European Physical Journal Web of Conferences, Vol. 18, Chemistry in Astrophysical Media, AstrOHP 2010, ed. T. Pino & E. Dartois, 3001
- Desert, F.-X., Boulanger, F., & Puget, J. L. 1990, A&A, 237, 215
- Desert, F. X., Boulanger, F., & Shore, S. N. 1986, A&A, 160, 295
- Devereux, N. A., Price, R., Wells, L. A., & Duric, N. 1994, AJ, 108, 1667
- Devereux, N. A. & Young, J. S. 1990, ApJ, 359, 42
- di Bartolomeo, A., Barbaro, G., & Perinotto, M. 1995, MNRAS, 277, 1279
- Dicker, S. R., Mason, B. S., Korngut, P. M., et al. 2009, ApJ, 705, 226
- Disney, M., Davies, J., & Phillipps, S. 1989, MNRAS, 239, 939
- Domingue, D. L., Keel, W. C., & White, III, R. E. 2000, ApJ, 545, 171

- Doty, S. D., Metzler, R. A., & Palotti, M. L. 2005, *MNRAS*, 362, 737
- Doyle, D., Pilbratt, G., & Tauber, J. 2009, *Proceedings of the IEEE*, 97, 1403
- Doyon, R. & Joseph, R. D. 1989, *MNRAS*, 239, 347
- Draine, B. T. 1988, *ApJ*, 333, 848
- Draine, B. T. 2003a, *ARA&A*, 41, 241
- Draine, B. T. 2003b, *ApJ*, 598, 1017
- Draine, B. T. 2004, in *Saas-Fee Advanced Course, Vol. 32, The Cold Universe*, ed. A. W. Blain, F. Combes, B. T. Draine, D. Pfenniger, & Y. Revaz, *Lecture Notes 2002 of the Swiss Society for Astronomy and Astrophysics (SSAA)* (Springer-Verlag), 213–304
- Draine, B. T. 2009a, in *Astronomical Society of the Pacific Conference Series, Vol. 414, Cosmic Dust - Near and Far*, ed. T. Henning, E. Grün, & J. Steinacker, 453
- Draine, B. T. 2009b, in *EAS Publications Series, Vol. 35, Interstellar Dust from Astronomical Observations to Fundamental Studies*, ed. F. Boulanger, C. Joblin, A. Jones, & S. Madden, 245–268
- Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, *ApJ*, 663, 866
- Draine, B. T. & Lee, H. M. 1984, *ApJ*, 285, 89
- Draine, B. T. & Li, A. 2001, *ApJ*, 551, 807
- Draine, B. T. & Li, A. 2007, *ApJ*, 657, 810
- Dressler, A. 1980, *ApJ*, 236, 351
- Drinkwater, M. J., Gregg, M. D., & Colless, M. 2001, *ApJ*, 548, L139
- Dunne, L., Eales, S., Edmunds, M., et al. 2000, *MNRAS*, 315, 115
- Dunne, L., Gomez, H. L., da Cunha, E., et al. 2011, *MNRAS*, 417, 1510
- Dupac, X., del Burgo, C., Bernard, J.-P., et al. 2003, *MNRAS*, 344, 105
- Dupac, X., Giard, M., Bernard, J.-P., et al. 2001, *ApJ*, 553, 604
- Dwek, E. 1986, *ApJ*, 302, 363
- Dwek, E. 2005, in *American Institute of Physics Conference Series, Vol. 761, The Spectral Energy Distributions of Gas-Rich Galaxies: Confronting Models with Data*, ed. C. C. Popescu & R. J. Tuffs, 103–122

- Eales, S., Dunne, L., Clements, D., et al. 2010, *PASP*, 122, 499
- Eales, S., Smith, M. W. L., Auld, R., et al. 2012, *ApJ*, 761, 168
- Edmunds, M. G. 2001, *MNRAS*, 328, 223
- Emsellem, E. 1995, *A&A*, 303, 673
- Emsellem, E., Dejonghe, H., & Bacon, R. 1999, *MNRAS*, 303, 495
- Emsellem, E., Monnet, G., & Bacon, R. 1994a, *A&A*, 285, 723
- Emsellem, E., Monnet, G., Bacon, R., & Nieto, J.-L. 1994b, *A&A*, 285, 739
- Engelbracht, C. W., Rieke, G. H., Gordon, K. D., et al. 2008, *ApJ*, 678, 804
- Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1998, *ApJ*, 503, 109
- Ferguson, H. C. 1989, *AJ*, 98, 367
- Ferrarese, L., Côté, P., Jordán, A., et al. 2006, *ApJS*, 164, 334
- Fischer, O., Henning, T., & Yorke, H. W. 1994, *A&A*, 284, 187
- Fitzpatrick, E. L. 1999, *PASP*, 111, 63
- Florido, E., Prieto, M., Battaner, E., et al. 1991, *A&A*, 242, 301
- Ford, G. P., Gear, W. K., Smith, M. W. L., et al. 2013, *ApJ*, 769, 55
- Foyle, K., Wilson, C. D., Mentuch, E., et al. 2012, *MNRAS*, 421, 2917
- Fritz, J., Franceschini, A., & Hatziminaoglou, E. 2006, *MNRAS*, 366, 767
- Fritz, J., Gentile, G., Smith, M. W. L., et al. 2012, *A&A*, 546, A34
- Fruchter, A. S. & Hook, R. N. 2002, *PASP*, 114, 144
- Galametz, M., Kennicutt, R. C., Albrecht, M., et al. 2012, *MNRAS*, 425, 763
- Galametz, M., Madden, S., Galliano, F., et al. 2009, *A&A*, 508, 645
- Galametz, M., Madden, S. C., Galliano, F., et al. 2010, *A&A*, 518, L55
- Galliano, F., Hony, S., Bernard, J.-P., et al. 2011, *A&A*, 536, A88
- Galliano, F., Madden, S. C., Jones, A. P., Wilson, C. D., & Bernard, J.-P. 2005, *A&A*, 434, 867

- Galliano, F., Madden, S. C., Jones, A. P., et al. 2003, *A&A*, 407, 159
- Gavazzi, G., Boselli, A., Donati, A., Franzetti, P., & Scodreggio, M. 2003, *A&A*, 400, 451
- Gavazzi, G., Boselli, A., Scodreggio, M., Pierini, D., & Belsole, E. 1999, *MNRAS*, 304, 595
- Gavazzi, G., Zaccardo, A., Sanvito, G., Boselli, A., & Bonfanti, C. 2004, *A&A*, 417, 499
- Genzel, R. & Cesarsky, C. J. 2000, *ARA&A*, 38, 761
- Giorgini, J. D., Yeomans, D. K., Chamberlin, A. B., et al. 1996, in *Bulletin of the American Astronomical Society*, Vol. 28, AAS/Division for Planetary Sciences Meeting Abstracts #28, 1158
- Girardi, M., Giuricin, G., Mardirossian, F., Mezzetti, M., & Boschini, W. 1998, *ApJ*, 505, 74
- Golombek, D., Miley, G. K., & Neugebauer, G. 1988, *AJ*, 95, 26
- Gomez, H. L., Baes, M., Cortese, L., et al. 2010, *A&A*, 518, L45
- Gómez, P. L., Nichol, R. C., Miller, C. J., et al. 2003, *ApJ*, 584, 210
- Gordon, K. D., Bailin, J., Engelbracht, C. W., et al. 2006, *ApJ*, 638, L87
- Gordon, K. D., Misselt, K. A., Witt, A. N., & Clayton, G. C. 2001, *ApJ*, 551, 269
- Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, *A&A*, 518, L3
- Grossi, M., Hunt, L. K., Madden, S., et al. 2010, *A&A*, 518, L52
- Guhathakurta, P. & Draine, B. T. 1989, *ApJ*, 345, 230
- Guthrie, B. N. G. 1992, *A&AS*, 93, 255
- Haas, M. 1998, *A&A*, 337, L1
- Haas, M., Lemke, D., Stickel, M., et al. 1998, *A&A*, 338, L33
- Haas, M., Müller, S. A. H., Bertoldi, F., et al. 2004, *A&A*, 424, 531
- Haas, T. & Makarenko, V. 2011, *European Physical Journal C*, 71, 1574
- Hauser, M. G., Arendt, R. G., Kelsall, T., et al. 1998, *ApJ*, 508, 25
- Haynes, M. P. & Giovanelli, R. 1984, *AJ*, 89, 758
- Helou, G., Lu, N. Y., Werner, M. W., Malhotra, S., & Silbermann, N. 2000, *ApJ*, 532, L21

- Heney, L. G. & Greenstein, J. L. 1941, *ApJ*, 93, 70
- Hernquist, L. 1990, *ApJ*, 356, 359
- Herschel, W. 1800, *Royal Society of London Philosophical Transactions Series I*, 90, 284
- Hildebrand, R. H. 1983, *QJRAS*, 24, 267
- Hobson, M. P. & Scheuer, P. A. G. 1993, *MNRAS*, 264, 145
- Holwerda, B. W., Allen, R. J., de Blok, W. J. G., et al. 2013, *Astronomische Nachrichten*, 334, 268
- Holwerda, B. W., Bianchi, S., Baes, M., et al. 2012a, in *IAU Symposium*, Vol. 284, *The Spectral Energy Distribution of Galaxies*, ed. R. J. Tuffs & C. C. Popescu, 128–131
- Holwerda, B. W., Bianchi, S., Böker, T., et al. 2012b, *A&A*, 541, L5
- Holwerda, B. W., Gonzalez, R. A., Allen, R. J., & van der Kruit, P. C. 2005a, *AJ*, 129, 1381
- Holwerda, B. W., González, R. A., van der Kruit, P. C., & Allen, R. J. 2005b, *A&A*, 444, 109
- Holwerda, B. W., Keel, W. C., & Bolton, A. 2007a, *AJ*, 134, 2385
- Holwerda, B. W., Keel, W. C., Williams, B., Dalcanton, J. J., & de Jong, R. S. 2009, *AJ*, 137, 3000
- Holwerda, B. W., Meyer, M., Regan, M., et al. 2007b, *AJ*, 134, 1655
- Houck, J. R., Charmandaris, V., Brandl, B. R., et al. 2004, *ApJS*, 154, 211
- Howk, J. C. 2012, in *EAS Publications Series*, Vol. 56, *The Role of the Disk-Halo Interaction in Galaxy Evolution: Outflow vs. Infall?*, ed. M. A. de Avillez, 291–298, arXiv:0904.4928
- Howk, J. C. & Savage, B. D. 1997, *AJ*, 114, 2463
- Howk, J. C. & Savage, B. D. 1999, *AJ*, 117, 2077
- Hubble, E. P. 1929, *ApJ*, 69, 103
- Hunt, L., Bianchi, S., & Maiolino, R. 2005, *A&A*, 434, 849
- Hunter, D. A. & Elmegreen, B. G. 2004, *AJ*, 128, 2170

- Ibar, E., Ivison, R. J., Cava, A., et al. 2010, MNRAS, 409, 38
- Impey, C. D. & He, X.-T. 1986, MNRAS, 221, 897
- Inoue, A. K. 2005, MNRAS, 359, 171
- Iono, D., Yun, M. S., & Ho, P. T. P. 2005, ApJS, 158, 1
- Irwin, J. A., Kennedy, H., Parkin, T., & Madden, S. 2007, A&A, 474, 461
- Irwin, J. A. & Madden, S. C. 2006, A&A, 445, 123
- Ivezic, Z., Groenewegen, M. A. T., Men'shchikov, A., & Szczerba, R. 1997, MNRAS, 291, 121
- Jadach, S. 2003, Computer Physics Communications, 152, 55
- Jadach, S. & Sawicki, P. 2007, Computer Physics Communications, 177, 441
- Jadach, S. & Skrzypek, M. 2006, Computer Physics Communications, 175, 511
- Jaffe, W. 1983, MNRAS, 202, 995
- Jaffe, W., Meisenheimer, K., Röttgering, H. J. A., et al. 2004, Nature, 429, 47
- Jarvis, B. J. 1986, AJ, 91, 65
- Jones, A. P. 2000, J. Geophys. Res., 105, 10257
- Jonsson, P. 2006, MNRAS, 372, 2
- Jonsson, P., Groves, B. A., & Cox, T. J. 2010, MNRAS, 403, 17
- Jordán, A., Blakeslee, J. P., Côté, P., et al. 2007, ApJS, 169, 213
- Just, A., Fuchs, B., & Wielen, R. 1996, A&A, 309, 715
- Juvela, M. 2005, A&A, 440, 531
- Juvela, M. & Padoan, P. 2003, A&A, 397, 201
- Kamphuis, P., Holwerda, B. W., Allen, R. J., Peletier, R. F., & van der Kruit, P. C. 2007, A&A, 471, L1
- Keel, W. C. & White, III, R. E. 2001a, AJ, 121, 1442
- Keel, W. C. & White, III, R. E. 2001b, AJ, 122, 1369
- Kenney, J., Beck, R., Helou, G., et al. 2006, Spitzer Proposal, 30945

- Kennicutt, R. C., Calzetti, D., Aniano, G., et al. 2011, *PASP*, 123, 1347
- Kennicutt, Jr., R. C. 1998, *ApJ*, 498, 541
- Kennicutt, Jr., R. C., Armus, L., Bendo, G., et al. 2003, *PASP*, 115, 928
- Kessler, M. F., Steinz, J. A., Anderegg, M. E., et al. 1996, *A&A*, 315, L27
- Koopmann, R. A., Haynes, M. P., & Catinella, B. 2006, *AJ*, 131, 716
- Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, *ApJS*, 182, 216
- Kovalev, Y. Y., Lister, M. L., Homan, D. C., & Kellermann, K. I. 2007, *ApJ*, 668, L27
- Kregel, M., van der Kruit, P. C., & de Grijs, R. 2002, *MNRAS*, 334, 646
- Krügel, E. 2003, *The physics of interstellar dust* (Institute of Physics Publishing)
- Kuchinski, L. E., Terndrup, D. M., Gordon, K. D., & Witt, A. N. 1998, *AJ*, 115, 1438
- Kuno, N., Sato, N., Nakanishi, H., et al. 2007, *PASJ*, 59, 117
- Kylafis, N. D. & Bahcall, J. N. 1987, *ApJ*, 317, 637
- Leroy, A. K., Bolatto, A., Gordon, K., et al. 2011, *ApJ*, 737, 12
- Lewis, I., Balogh, M., De Propriis, R., et al. 2002, *MNRAS*, 334, 673
- Li, A. & Draine, B. T. 2001, *ApJ*, 554, 778
- Lindblad, B. 1935, *Nature*, 135, 133
- Lindblad, B. 1956, *Stockholms Observatoriums Annaler*, 19
- Lisenfeld, U., Israel, F. P., Stil, J. M., & Sievers, A. 2002, *A&A*, 382, 860
- Lisenfeld, U., Verdes-Montenegro, L., Sulentic, J., et al. 2007, *A&A*, 462, 507
- Longdon, N., ed. 1984, *ESA Special Publication*, Vol. 1070, *European Space Science : Horizon 2000*
- Lucy, L. B. 1999, *A&A*, 344, 282
- MacKenty, J. W., Skinner, C., Calzetti, D., & Axon, D. J. 1997, *NICMOS Instrument Handbook*, Version 2.0 (Baltimore: STScI)
- Madden, S. C. 2002, *Ap&SS*, 281, 247
- Magrini, L., Bianchi, S., Corbelli, E., et al. 2011, *A&A*, 535, A13

- Maoz, D. 1995, *ApJ*, 455, L115
- Maraston, C. 1998, *MNRAS*, 300, 872
- Maraston, C. 2005, *MNRAS*, 362, 799
- Marleau, F. R., Noriega-Crespo, A., Misselt, K. A., et al. 2006, *ApJ*, 646, 929
- Martin, A. M., Papastergis, E., Giovanelli, R., et al. 2010, *ApJ*, 723, 1359
- Martin, P. G. 1978, *Cosmic dust. Its impact on astronomy* (Clarendon Press)
- Mathis, J. S. 1990, *ARA&A*, 28, 37
- Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, *A&A*, 128, 212
- Matthews, L. D. & Wood, K. 2001, *ApJ*, 548, 150
- Mattila, K. 1970, *A&A*, 9, 53
- McConnachie, A. W., Irwin, M. J., Ferguson, A. M. N., et al. 2005, *MNRAS*, 356, 979
- Mei, S., Blakeslee, J. P., Côté, P., et al. 2007, *ApJ*, 655, 144
- Meisenheimer, K., Roeser, H.-J., & Schloetelburg, M. 1996, *A&A*, 307, 61
- Mentuch Cooper, E., Wilson, C. D., Foyle, K., et al. 2012, *ApJ*, 755, 165
- Meny, C., Gromov, V., Boudet, N., et al. 2007, *A&A*, 468, 171
- Metropolis, N. 1987, *Los Alamos Science*
- Metropolis, N. & Ulam, S. 1949, *Journal of the American Statistical Association*, 44, pp. 335
- Mie, G. 1908, *Annalen der Physik*, 330, 377
- Mihos, J. C., Harding, P., Feldmeier, J., & Morrison, H. 2005, *ApJ*, 631, L41
- Miller, S. T. & Veilleux, S. 2003, *ApJS*, 148, 383
- Min, M., Hovenier, J. W., & de Koter, A. 2005, *A&A*, 432, 909
- Misiriotis, A., Popescu, C. C., Tuffs, R., & Kylafis, N. D. 2001, *A&A*, 372, 775
- Misselt, K. A., Gordon, K. D., Clayton, G. C., & Wolff, M. J. 2001, *ApJ*, 551, 277
- Monnet, G., Bacon, R., & Emsellem, E. 1992, *A&A*, 253, 366

- Montalto, M., Seitz, S., Riffeser, A., et al. 2009, *A&A*, 507, 283
- Montier, L. A. & Giard, M. 2005, *A&A*, 439, 35
- Morrison, H. L., Boroson, T. A., & Harding, P. 1994, *AJ*, 108, 1191
- Moshir, M., Copan, G., Conrow, T., et al. 1993, *VizieR Online Data Catalog*, 2156, 0
- Moshir, M., Kopan, G., Conrow, T., et al. 1990, in *Bulletin of the American Astronomical Society*, Vol. 22, 1325
- Muñoz-Mateos, J. C., Gil de Paz, A., Boissier, S., et al. 2009, *ApJ*, 701, 1965
- Murakami, H., Baba, H., Barthel, P., et al. 2007, *PASJ*, 59, 369
- Nedialkov, P., Berkhuijsen, E. M., Nieten, C., & Haas, M. 2000, in *WE-Heraeus Seminar*, Vol. 232, *The interstellar medium in M31 and M33*, ed. E. M. Berkhuijsen, R. Beck, & R. A. M. Walterbos, 85–88
- Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, *ApJ*, 278, L1
- Niccolini, G., Woitke, P., & Lopez, B. 2003, *A&A*, 399, 703
- Nieten, C., Neininger, N., Guélin, M., et al. 2006, *A&A*, 453, 459
- Oliver, S. J., Wang, L., Smith, A. J., et al. 2010, *A&A*, 518, L21
- Oosterloo, T. & van Gorkom, J. 2005, *A&A*, 437, L19
- Ott, S. 2010, in *Astronomical Society of the Pacific Conference Series*, Vol. 434, *Astronomical Data Analysis Software and Systems XIX*, ed. Y. Mizumoto, K.-I. Morita, & M. Ohishi, 139
- Paolillo, M., Fabbiano, G., Peres, G., & Kim, D.-W. 2002, *ApJ*, 565, 883
- Pascucci, I., Wolf, S., Steinacker, J., et al. 2004, *A&A*, 417, 793
- Paturel, G., Petit, C., Prugniel, P., et al. 2003, *A&A*, 412, 45
- Pendleton, Y. J. & Allamandola, L. J. 2002, *ApJS*, 138, 75
- Pérez García, A. M. & Rodríguez Espinosa, J. M. 2001, *ApJ*, 557, 39
- Perlman, E. S., Biretta, J. A., Sparks, W. B., Macchetto, F. D., & Leahy, J. P. 2001, *ApJ*, 551, 206
- Perlman, E. S., Mason, R. E., Packham, C., et al. 2007, *ApJ*, 663, 808

- Perlman, E. S. & Wilson, A. S. 2005, *ApJ*, 627, 140
- Peterson, C. J., Ford, Jr., W. K., & Rubin, V. C. 1977, *AJ*, 82, 32
- Piazzo, L., Ikhenade, D., Natoli, P., et al. 2012, *IEEE Transactions on Image Processing*, 21, 3687
- Pierini, D., Gordon, K. D., Witt, A. N., & Madsen, G. J. 2004, *ApJ*, 617, 1022
- Pilbratt, G. L. 2008, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7010, *Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter*, ed. J. M. Oschmann, Jr., M. W. M. de Graauw, & H. A. MacEwen
- Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, *A&A*, 518, L1
- Pildis, R. A., Bregman, J. N., & Schombert, J. M. 1994, *ApJ*, 427, 160
- Pinte, C., Ménard, F., Duchêne, G., & Bastien, P. 2006, *A&A*, 459, 797
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2011, *A&A*, 536, A7
- Plummer, H. C. 1911, *MNRAS*, 71, 460
- Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, *A&A*, 518, L2
- Pohlen, M., Cortese, L., Smith, M. W. L., et al. 2010, *A&A*, 518, L72
- Popescu, C. C., Misiriotis, A., Kylafis, N. D., Tuffs, R. J., & Fischera, J. 2000a, *A&A*, 362, 138
- Popescu, C. C. & Tuffs, R. J. 2002, *MNRAS*, 335, L41
- Popescu, C. C. & Tuffs, R. J. 2003, *A&A*, 410, L21
- Popescu, C. C., Tuffs, R. J., Dopita, M. A., et al. 2011, *A&A*, 527, A109
- Popescu, C. C., Tuffs, R. J., Fischera, J., & Völk, H. 2000b, *A&A*, 354, 480
- Popesso, P., Magnelli, B., Buttiglione, S., et al. 2012, *arXiv:1211.4257*
- Popović, L. Č., Jovanović, P., Stalevski, M., et al. 2012, *A&A*, 538, A107
- Puget, J. L. & Leger, A. 1989, *ARA&A*, 27, 161
- Puget, J. L., Leger, A., & Boulanger, F. 1985, *A&A*, 142, L19
- Purcell, E. M. & Pennypacker, C. R. 1973, *ApJ*, 186, 705

- Renzini, A. 1997, *ApJ*, 488, 35
- Rice, W., Lonsdale, C. J., Soifer, B. T., et al. 1988, *ApJS*, 68, 91
- Rigby, E. E., Maddox, S. J., Dunne, L., et al. 2011, *MNRAS*, 415, 2336
- Rines, K. & Diaferio, A. 2006, *AJ*, 132, 1275
- Roark, T., Roark, B., & Collins, II, G. W. 1974, *ApJ*, 190, 67
- Robberto, M., Sivaramakrishnan, A., Bacinski, J. J., et al. 2000, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4013, UV, Optical, and IR Space Telescopes and Instruments, ed. J. B. Breckinridge & P. Jakobsen, 386–393
- Roussel, H. 2013, submitted to *PASP* (arXiv:1205.2576)
- Roussel, H., Wilson, C. D., Vigroux, L., et al. 2010, *A&A*, 518, L66
- Rowan-Robinson, M., Helou, G., & Walker, D. 1987, *MNRAS*, 227, 589
- Rybicki, G. B. & Lightman, A. P. 1979, *Radiative processes in astrophysics* (John Wiley & Sons, Inc.)
- Sabatini, S., Davies, J., Scaramella, R., et al. 2003, *MNRAS*, 341, 981
- Sanchez-Saavedra, M. L., Battaner, E., & Florido, E. 1990, *MNRAS*, 246, 458
- Sancisi, R. 1976, *A&A*, 53, 159
- Sandage, A. & Bedke, J. 1994, *The Carnegie Atlas of Galaxies. Volumes I, II.* (Carnegie Institution of Washington Publ.)
- Sandage, A., Binggeli, B., & Tammann, G. A. 1985, *AJ*, 90, 1759
- Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, *AJ*, 126, 1607
- Scharf, C. A., Zurek, D. R., & Bureau, M. 2005, *ApJ*, 633, 154
- Schechtman-Rook, A., Bershadsky, M. A., & Wood, K. 2012a, *ApJ*, 746, 70
- Schechtman-Rook, A., Bershadsky, M. A., Wood, K., & Robitaille, T. P. 2012b, in *IAU Symposium*, Vol. 284, *IAU Symposium*, ed. R. J. Tuffs & C. C. Popescu, 104–106

- Sein, E., Toulemont, Y., Safa, F., et al. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4850, IR Space Telescopes and Instruments, ed. J. C. Mather, 606–618
- Semionov, D. & Vansevičius, V. 2005, *Baltic Astronomy*, 14, 543
- Sersic, J. L. 1968, *Atlas de galaxias australes* (Córdoba, Argentina: Observatorio Astronómico, Universidad Nacional de Córdoba)
- Shang, Z., Zheng, Z., Brinks, E., et al. 1998, *ApJ*, 504, L23
- Shi, Y., Rieke, G. H., Hines, D. C., Gordon, K. D., & Egami, E. 2007, *ApJ*, 655, 781
- Sibthorpe, B., Waskett, T. J., & Griffin, M. J. 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 6270, Observatory Operations: Strategies, Processes, and Systems, ed. D. R. Silva & R. E. Doxsey
- Siebenmorgen, R., Kruegel, E., & Mathis, J. S. 1992, *A&A*, 266, 501
- Simionescu, A., Werner, N., Finoguenov, A., Böhringer, H., & Brüggen, M. 2008, *A&A*, 482, 97
- Skillman, E. D., Kennicutt, Jr., R. C., Shields, G. A., & Zaritsky, D. 1996, *ApJ*, 462, 147
- Smith, J. D. T., Draine, B. T., Dale, D. A., et al. 2007, *ApJ*, 656, 770
- Smith, M. W. L., Eales, S. A., Gomez, H. L., et al. 2012, *ApJ*, 756, 40
- Smith, M. W. L., Vlahakis, C., Baes, M., et al. 2010, *A&A*, 518, L51
- Soifer, B. T., Boehmer, L., Neugebauer, G., & Sanders, D. B. 1989, *AJ*, 98, 766
- Soifer, B. T., Sanders, D. B., Madore, B. F., et al. 1987, *ApJ*, 320, 238
- Sparks, W. B., Donahue, M., Jordán, A., Ferrarese, L., & Côté, P. 2004, *ApJ*, 607, 294
- Sparks, W. B., Ford, H. C., & Kinney, A. L. 1993, *ApJ*, 413, 531
- Springel, V. 2010, *MNRAS*, 401, 791
- Stalevski, M., Fritz, J., Baes, M., Nakos, T., & Popović, L. Č. 2012, *MNRAS*, 420, 2756
- Stamatellos, D. & Whitworth, A. P. 2003, *A&A*, 407, 941
- Stansberry, J. A., Gordon, K. D., Bhattacharya, B., et al. 2007, *PASP*, 119, 1038
- Starck, J. L., Abergel, A., Aussel, H., et al. 1999, *A&AS*, 134, 135

- Starck, J.-L. & Murtagh, F. 1998, *PASP*, 110, 193
- Starck, J.-L., Murtagh, F., & Bijaoui, A. 1995, in *Astronomical Society of the Pacific Conference Series*, Vol. 77, *Astronomical Data Analysis Software and Systems IV*, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes, 279–288
- Starck, J.-L., Murtagh, F., Pirenne, B., & Albrecht, M. 1996, *PASP*, 108, 446
- Steinacker, J., Bacmann, A., & Henning, T. 2002, *J. Quant. Spec. Radiat. Transf.*, 75, 765
- Steinacker, J., Baes, M., & Gordon, K. D. 2013, *ARA&A*, 51, arXiv:1303.4998
- Steinacker, J., Henning, T., Bacmann, A., & Semenov, D. 2003, *A&A*, 401, 405
- Stenholm, L. G., Störzer, H., & Wehrse, R. 1991, *J. Quant. Spec. Radiat. Transf.*, 45, 47
- Stickel, M., Lemke, D., Klaas, U., Krause, O., & Egner, S. 2004, *A&A*, 422, 39
- Stickel, M., Lemke, D., Mattila, K., Haikala, L. K., & Haas, M. 1998, *A&A*, 329, 55
- Strong, A. W. & Mattox, J. R. 1996, *A&A*, 308, L21
- Struck, C., Appleton, P., Charmandaris, V., Reach, W., & Smith, B. 2004, *Spitzer Proposal*, 3247
- Tabatabaei, F. S. & Berkhuijsen, E. M. 2010, *A&A*, 517, A77
- Tan, J. C., Beuther, H., Walter, F., & Blackman, E. G. 2008, *ApJ*, 689, 775
- Thilker, D. A., Braun, R., Walterbos, R. A. M., et al. 2004, *ApJ*, 601, L39
- Thompson, T. W. J., Howk, J. C., & Savage, B. D. 2004, *AJ*, 128, 662
- Thuan, T. X., Sauvage, M., & Madden, S. 1999, *ApJ*, 516, 783
- Tielens, A. G. G. M. 2008, *ARA&A*, 46, 289
- Trumpler, R. J. 1930, *PASP*, 42, 214
- Trundle, C., Dufton, P. L., Lennon, D. J., Smartt, S. J., & Urbaneja, M. A. 2002, *A&A*, 395, 519
- Tuffs, R. J., Popescu, C. C., Pierini, D., et al. 2002, *ApJS*, 139, 37
- van den Bosch, R. C. E., van de Ven, G., Verolme, E. K., Cappellari, M., & de Zeeuw, P. T. 2008, *MNRAS*, 385, 647
- van der Vorst, H. 1992, *SIAM Journal on Scientific and Statistical Computing*, 13, 631

- Verstappen, J., Fritz, J., Baes, M., et al. 2013, *A&A*, in press (arXiv:1305.3130)
- Viana, A., Wiklind, T., Koekemoer, A., et al. 2009, *NICMOS Instrument Handbook*, Version 11.0 (Baltimore: STScI)
- Vidal, E. & Baes, M. 2007, *Baltic Astronomy*, 16, 101
- Vlahakis, C., Dunne, L., & Eales, S. 2005, *MNRAS*, 364, 1253
- Wainscoat, R. J., Freeman, K. C., & Hyland, A. R. 1989, *ApJ*, 337, 163
- Walterbos, R. A. M. & Kennicutt, Jr., R. C. 1988, *A&A*, 198, 61
- Walterbos, R. A. M. & Schwoering, P. B. W. 1987, *A&A*, 180, 27
- Waskett, T. J., Sibthorpe, B., Griffin, M. J., & Chanial, P. F. 2007, *MNRAS*, 381, 1583
- Weingartner, J. C. & Draine, B. T. 2001, *ApJ*, 548, 296
- Weissman, M. B. 1988, *Reviews of Modern Physics*, 60, 537
- Welch, G. A., Sage, L. J., & Mitchell, G. F. 1998, *ApJ*, 499, 209
- Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, *ApJS*, 154, 1
- Werner, N., Simionescu, A., Million, E. T., et al. 2010, *MNRAS*, 407, 2063
- Whaley, C. H., Irwin, J. A., Madden, S. C., Galliano, F., & Bendo, G. J. 2009, *MNRAS*, 395, 97
- Whitney, B. A. 2011, *Bulletin of the Astronomical Society of India*, 39, 101
- Witt, A. N. 1977, *ApJS*, 35, 1
- Witt, A. N. & Gordon, K. D. 1996, *ApJ*, 463, 681
- Witt, A. N. & Gordon, K. D. 2000, *ApJ*, 528, 799
- Witt, A. N. & Stephens, T. C. 1974, *AJ*, 79, 948
- Witt, A. N., Thronson, Jr., H. A., & Capuano, Jr., J. M. 1992, *ApJ*, 393, 611
- Wolf, S. 2003a, *ApJ*, 582, 859
- Wolf, S. 2003b, *Computer Physics Communications*, 150, 99
- Wolf, S., Fischer, O., & Pfau, W. 1998, *A&A*, 340, 103
- Wood, K., Whitney, B. A., Robitaille, T., & Draine, B. T. 2008, *ApJ*, 688, 1118

- Wright, E. L., Chen, X., Odegard, N., et al. 2009, *ApJS*, 180, 283
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, 140, 1868
- Xilouris, E. M., Alton, P. B., Davies, J. I., et al. 1998, *A&A*, 331, 894
- Xilouris, E. M., Byun, Y. I., Kylafis, N. D., Paleologou, E. V., & Papamastorakis, J. 1999, *A&A*, 344, 868
- Xilouris, E. M., Kylafis, N. D., Papamastorakis, J., Paleologou, E. V., & Haerendel, G. 1997, *A&A*, 325, 135
- Xilouris, E. M., Madden, S. C., Galliano, F., Vigroux, L., & Sauvage, M. 2004, *A&A*, 416, 41
- Xilouris, E. M., Tabatabaei, F. S., Boquien, M., et al. 2012, *A&A*, 543, A74
- Yamamura, I., Makiuti, S., Ikeda, N., et al. 2010, *VizieR Online Data Catalog*, 2298, 0
- Yusef-Zadeh, F., Morris, M., & White, R. L. 1984, *ApJ*, 278, 186
- Zitrin, A., Brosch, N., & Bilenko, B. 2009, *MNRAS*, 399, 924
- Zubko, V., Dwek, E., & Arendt, R. G. 2004, *ApJS*, 152, 211
- Zwicky, F. 1957, *PASP*, 69, 518

List of publications

Refereed publications

1. *HERschel* Observations of Edge-on Spirals (*HEROES*). I: Far-infrared morphology and dust mass determination
Verstappen J., Fritz J., Baes M., Smith M. W. L., Allaert F., Bianchi S., Blommaert J. A. D. L., De Geyter G., De Looze I., Gentile G., Gordon K. D., Holwerda B. W., Viaene S., Xilouris E. M.
Astronomy & Astrophysics, in press (arXiv:1305.3130)
2. *Herschel* Exploitation of Local Galaxy Andromeda (*HELGA*). III: The Star Formation Law in M31
Ford G. P., Gear W. K., Smith M. W. L., Eales S. A., Baes M., Bendo G. J., Boquien M., Boselli A., Cooray A. R., De Looze I., Fritz J., Gentile G., Gomez H. L., Gordon K. D., Kirk J., Lebouteiller V., O'Halloran B., Spinoglio L., Verstappen J., Wilson C. D.
The Astrophysical Journal, **769**, 55 (2013)
3. The *Herschel* Virgo Cluster Survey. XII. FIR properties of optically selected Virgo cluster galaxies
Auld R., Bianchi S., Smith M. W. L., Davies J. I., Bendo G. J., di Serego S. A., Cortese L., Baes M., Bomans D. J., Boquien M., Boselli A., Ciesla L., Clemens M., Corbelli E., De Looze I., Fritz J., Gavazzi G., Pappalardo C., Grossi M., Hunt L. K., Madden S., Magrini L., Pohlen M., Verstappen J., Vlahakis C., Xilouris E. M., Zibetti S.
Monthly Notices of the Royal Astronomical Society, **428**, 1880 (2013)
4. The *Herschel* Fornax Cluster Survey. I. The bright galaxy sample
Davies J. I., Bianchi S., Baes M., Boselli A., Ciesla L., Clemens M., Davis T. A., De Looze I., Alighieri S. d. S., Fuller C., Fritz J., Hunt L. K., Serra P., Smith M. W. L., Verstappen J., Vlahakis C., Xilouris E. M., Bomans D., Hughes T., Garcia-Appadoo D., Madden S.
Monthly Notices of the Royal Astronomical Society, **428**, 834 (2013)

5. The dust energy balance in the edge-on spiral galaxy NGC 4565
De Looze I., Baes M., Bendo G. J., Ciesla L., Cortese L., de Geyter G., Groves B., Boquien M., Boselli A., Brondeel L., Cooray A., Eales S., Fritz J., Galliano F., Gentile G., Gordon K. D., Hony S., Law K.-H., Madden S. C., Sauvage M., Smith M. W. L., Spinoglio L., Verstappen J.
Monthly Notices of the Royal Astronomical Society, **427**, 2797 (2012)
6. Can Dust Emission be Used to Estimate the Mass of the Interstellar Medium in Galaxies—A Pilot Project with the *Herschel* Reference Survey
Eales S., Smith M. W. L., Auld R., Baes M., Bendo G. J., Bianchi S., Boselli A., Ciesla L., Clements D., Cooray A., Cortese L., Davies J., De Looze I., Galametz M., Gear W., Gentile G., Gomez H., Fritz J., Hughes T., Madden S., Magrini L., Pohlen M., Spinoglio L., Verstappen J., Vlahakis C., Wilson C. D.
The Astrophysical Journal, **761**, 168 (2012)
7. The *Herschel* Exploitation of Local Galaxy Andromeda (HELGA). I. Global far-infrared and sub-mm morphology
Fritz J., Gentile G., Smith M. W. L., Gear W. K., Braun R., Duval J. R., Bendo G. J., Baes M., Eales S. A., Verstappen J., Blommaert J. A. D. L., Boquien M., Boselli A., Clements D., Cooray A. R., Cortese L., De Looze I., Ford G. P., Galliano F., Gomez H. L., Gordon K. D., Lebouteiller V., O'Halloran B., Kirk J., Madden S. C., Page M. J., Remy A., Roussel H., Spinoglio L., Thilker D., Vaccari M., Wilson C. D., Waelkens C.
Astronomy & Astrophysics, **546**, A34 (2012)
8. The *Herschel* Exploitation of Local Galaxy Andromeda (HELGA). II. Dust and Gas in Andromeda
Smith M. W. L., Eales S. A., Gomez H. L., Roman-Duval J., Fritz J., Braun R., Baes M., Bendo G. J., Blommaert J. A. D. L., Boquien M., Boselli A., Clements D. L., Cooray A. R., Cortese L., De Looze I., Ford G. P., Gear W. K., Gentile G., Gordon K. D., Kirk J., Lebouteiller V., Madden S., Mentuch E., O'Halloran B., Page M. J., Schulz B., Spinoglio L., Verstappen J., Wilson C. D., Thilker D. A.
The Astrophysical Journal, **756**, 40 (2012)
9. The *Herschel* Virgo Cluster Survey. XI. Environmental effects on molecular gas and dust in spiral disks
Pappalardo C., Bianchi S., Corbelli E., Giovanardi C., Hunt L., Bendo G. J., Boselli A., Cortese L., Magrini L., Zibetti S., di Serego Alighieri S., Davies J., Baes M., Ciesla L., Clemens M., De Looze I., Fritz J., Grossi M., Pohlen M., Smith M. W. L., Verstappen J., Vlahakis C.
Astronomy & Astrophysics, **545**, A75 (2012)

10. *Herschel* and JCMT observations of the early-type dwarf galaxy NGC 205
De Looze I., Baes M., Parkin T. J., Wilson C. D., Bendo G. J., Boquien M., Boselli A., Cooray A., Cormier D., Fritz J., Galliano F., Gear W., Gentile G., Lebouteiller V., Madden S. C., Roussel H., Sauvage M., Smith M. W. L., Spinoglio L., Verstappen J., Young L.
Monthly Notices of the Royal Astronomical Society, **423**, 2359 (2012)
11. The *Herschel* Virgo Cluster Survey. X. The relationship between cold dust and molecular gas content in Virgo spirals
Corbelli E., Bianchi S., Cortese L., Giovanardi C., Magrini L., Pappalardo C., Boselli A., Bendo G. J., Davies J., Grossi M., Madden S. C., Smith M. W. L., Vlahakis C., Auld R., Baes M., De Looze I., Fritz J., Pohlen M., Verstappen J.
Astronomy & Astrophysics, **542**, A32 (2012)
12. The *Herschel* Reference Survey: Dust in Early-type Galaxies and across the Hubble Sequence
Smith M. W. L., Gomez H. L., Eales S. A., Ciesla L., Boselli A., Cortese L., Bendo G. J., Baes M., Bianchi S., Clemens M., Clements D. L., Cooray A. R., Davies J. I., De Looze I., di Serego Alighieri S., Fritz J., Gavazzi G., Gear W. K., Madden S., Mentuch E., Panuzzo P., Pohlen M., Spinoglio L., Verstappen J., Vlahakis C., Wilson C. D., Xilouris E. M.
The Astrophysical Journal, **748**, 123 (2012)
13. The *Herschel* Virgo Cluster Survey. VIII. The Bright Galaxy Sample
Davies J. I., Bianchi S., Cortese L., Auld R., Baes M., Bendo G. J., Boselli A., Ciesla L., Clemens M., Corbelli E., De Looze I., Alighieri S. D. S., Fritz J., Gavazzi G., Pappalardo C., Grossi M., Hunt L. K., Madden S., Magrini L., Pohlen M., Smith M. W. L., Verstappen J., Vlahakis C.
Monthly Notices of the Royal Astronomical Society, **419**, 3505 (2012)
14. Panchromatic radiative transfer modelling of stars and dust in the Sombrero galaxy
De Looze I., Baes M., Fritz J., Verstappen J.
Monthly Notices of the Royal Astronomical Society, **419**, 895 (2012)
15. The *Herschel* Virgo Cluster Survey. IX. Dust-to-gas mass ratio and metallicity gradients in four Virgo spiral galaxies
Magrini L., Bianchi S., Corbelli E., Cortese L., Hunt L., Smith M., Vlahakis C., Davies J., Bendo G. J., Baes M., Boselli A., Clemens M., Casasola V., De Looze I., Fritz J., Giovanardi C., Grossi M., Hughes T., Madden S., Pappalardo C., Pohlen M., di Serego Alighieri S., Verstappen J.
Astronomy & Astrophysics, **535**, A13 (2011)

16. Efficient Three-dimensional NLTE Dust Radiative Transfer with SKIRT
Baes M., Verstackpen J., De Looze I., Fritz J., Saffly W., Vidal Pérez E., Stalevski M., Valcke S.
The Astrophysical Journal Supplement Series, **196**, 22 (2011)
17. The GALEX Ultraviolet Virgo Cluster Survey (GUViCS). I. The UV luminosity function of the central 12 sq. deg
Boselli A., Boissier S., Heinis S., Cortese L., Ilbert O., Hughes T., Cucciati O., Davies J., Ferrarese L., Giovanelli R., Haynes M. P., Baes M., Balkowski C., Brosch N., Chapman S. C., Charmandaris V., Clemens M. S., Dariush A., De Looze I., di Serego Alighieri S., Duc P.-A., Durrell P. R., Emsellem E., Erben T., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Grossi M., Jordán A., Hess K. M., Huertas-Company M., Hunt L. K., Kent B. R., Lambas D. G., Lançon A., MacArthur L. A., Madden S. C., Magrini L., Mei S., Momjian E., Olowin R. P., Papastergis E., Smith M. W. L., Solanes J. M., Spector O., Spekkens K., Taylor J. E., Valotto C., van Driel W., Verstackpen J., Vlahakis C., Vollmer B., Xilouris E. M.
Astronomy & Astrophysics, **528**, A107 (2011)
18. FIR colours and SEDs of nearby galaxies observed with *Herschel*
Boselli A., Ciesla L., Buat V., Cortese L., Auld R., Baes M., Bendo G. J., Bianchi S., Bock J., Bomans D. J., Bradford M., Castro-Rodriguez N., Chanial P., Charlot S., Clemens M., Clements D., Corbelli E., Cooray A., Cormier D., Dariush A., Davies J., De Looze I., di Serego Alighieri S., Dwek E., Eales S., Elbaz D., Fadda D., Fritz J., Galametz M., Galliano F., Garcia-Appadoo D. A., Gavazzi G., Gear W., Giovannardi C., Glenn J., Gomez H., Griffin M., Grossi M., Honý S., Hughes T. M., Hunt L., Isaak K., Jones A., Levenson L., Lu N., Madden S. C., O'Halloran B., Okumura K., Oliver S., Page M., Panuzzo P., Papageorgiou A., Parkin T., Perez-Fournon I., Pierini D., Pohlen M., Rangwala N., Rigby E., Roussel H., Rykala A., Sabatini S., Sacchi N., Sauvage M., Schulz B., Schirm M., Smith M. W. L., Spinoglio L., Stevens J., Sundar S., Symeonidis M., Trichas M., Vaccari M., Verstackpen J., Vigroux L., Vlahakis C., Wilson C., Wozniak H., Wright G., Xilouris E. M., Zeilinger W., Zibetti S.
Astronomy & Astrophysics, **518**, L61 (2010)
19. The *Herschel* Virgo Cluster Survey. VII. Dust in cluster dwarf elliptical galaxies
De Looze I., Baes M., Zibetti S., Fritz J., Cortese L., Davies J. I., Verstackpen J., Bendo G. J., Bianchi S., Clemens M., Bomans D. J., Boselli A., Corbelli E., Dariush A., di Serego Alighieri S., Fadda D., Garcia-Appadoo D. A., Gavazzi G., Giovannardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Vlahakis C., Xilouris E. M.
Astronomy & Astrophysics, **518**, L54 (2010)

20. The *Herschel* Virgo Cluster Survey. VI. The far-infrared view of M87
 Baes M., Clemens M., Xilouris E. M., Fritz J., Cotton W. D., Davies J. I., Bendo G. J., Bianchi S., Cortese L., De Looze I., Pohlen M., Verstappen J., Böhringer H., Bomans D. J., Boselli A., Corbelli E., Dariush A., di Serego Alighieri S., Fadda D., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Sabatini S., Smith M. W. L., Vlahakis C., Zibetti S.
Astronomy & Astrophysics, **518**, L53 (2010)
21. The *Herschel* Virgo Cluster Survey. V. Star-forming dwarf galaxies - dust in metal-poor environments
 Grossi M., Hunt L. K., Madden S., Vlahakis C., Bomans D. J., Baes M., Bendo G. J., Bianchi S., Boselli A., Clemens M., Corbelli E., Cortese L., Dariush A., Davies J. I., De Looze I., di Serego Alighieri S., Fadda D., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Hughes T. M., Jones A. P., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Verstappen J., Xilouris E. M., Zibetti S.
Astronomy & Astrophysics, **518**, L52 (2010)
22. The *Herschel* Virgo Cluster Survey. IV. Resolved dust analysis of spiral galaxies
 Smith M. W. L., Vlahakis C., Baes M., Bendo G. J., Bianchi S., Bomans D. J., Boselli A., Clemens M., Corbelli E., Cortese L., Dariush A., Davies J. I., De Looze I., di Serego Alighieri S., Fadda D., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Pohlen M., Sabatini S., Verstappen J., Xilouris E. M., Zibetti S.
Astronomy & Astrophysics, **518**, L51 (2010)
23. The *Herschel* Virgo Cluster Survey. III. A constraint on dust grain lifetime in early-type galaxies
 Clemens M. S., Jones A. P., Bressan A., Baes M., Bendo G. J., Bianchi S., Bomans D. J., Boselli A., Corbelli E., Cortese L., Dariush A., Davies J. I., De Looze I., di Serego Alighieri S., Fadda D., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Madden S., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Verstappen J., Vlahakis C., Xilouris E. M., Zibetti S.
Astronomy & Astrophysics, **518**, L50 (2010)
24. The *Herschel* Virgo Cluster Survey. II. Truncated dust disks in H I-deficient spirals
 Cortese L., Davies J. I., Pohlen M., Baes M., Bendo G. J., Bianchi S., Boselli A., De Looze I., Fritz J., Verstappen J., Bomans D. J., Clemens M., Corbelli E., Dariush A., di Serego Alighieri S., Fadda D., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Sabatini S., Smith M. W. L., Vlahakis C., Xilouris E. M., Zibetti S.

Astronomy & Astrophysics, **518**, L49 (2010)

25. The *Herschel* Virgo Cluster Survey. I. Luminosity function

Davies J. I., Baes M., Bendo G. J., Bianchi S., Bomans D. J., Boselli A., Clemens M., Corbelli E., Cortese L., Dariush A., De Looze I., di Serego Alighieri S., Fadda D., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Verstappen J., Vlahakis C., Xilouris E. M., Zibetti S.

Astronomy & Astrophysics, **518**, L48 (2010)

Non-refereed publications

1. A detailed dust energy balance study of the Sombrero galaxy

De Looze I., Baes M., Fritz J., Gentile G., Verstappen J.

The spectral energy distribution of galaxies (eds. R. J. Tuffs & C. C. Popescu), *Proceedings of IAU*, **284**, 92 (2012)

2. Dust Content of Virgo Star-Forming Dwarf Galaxies

Grossi M., Hunt L. K., Madden S., Vlahakis C., Bomans D. J., Baes M., Bendo G. J., Bianchi S., Boselli A., Clemens M., Corbelli E., Cortese L., Dariush A., Davies J. I., De Looze I., di Serego Alighieri S., Fadda D., Fritz J., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Hughes T. M., Jones A. P., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Verstappen J., Xilouris E. M., Zibetti S.

Dwarf galaxies: keys to galaxy formation and evolution (eds. P. Papaderos, S. Recchi & G. Hensler), *Astrophysics and Space Science Proceedings*, 289 (2012)

3. Dust in Cluster Dwarf Elliptical Galaxies

De Looze I., Baes M., Fritz J., Verstappen J., Bendo G. J., Bianchi S., Bomans D. J., Boselli A., Clemens M., Corbelli E., Cortese L., Dariush A., Davies J. I., di Serego Alighieri S., Fadda D., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Magrini L., Pierini D., Pohlen M., Sabatini S., Smith M. W. L., Vlahakis C., Xilouris E. M., Zibetti S.

Dwarf galaxies: keys to galaxy formation and evolution (eds. P. Papaderos, S. Recchi & G. Hensler), *Astrophysics and Space Science Proceedings*, 163 (2012)

4. The far-infrared view of M 87 as seen by the *Herschel* Space Observatory

Baes M., Clemens M., Xilouris E. M., Fritz J., Cotton W. D., Davies J. I., Bendo G. J., Bianchi S., Cortese L., De Looze I., Pohlen M., Verstappen J., Böhringer H., Bomans D. J., Boselli A., Corbelli E., Dariush A., di Serego Alighieri S., Fadda D., Garcia-Appadoo D. A., Gavazzi G., Giovanardi C., Grossi M., Hughes T. M., Hunt L. K., Jones A. P., Madden S., Pierini D., Sabatini S., Smith M. W. L., Vlahakis

C., Zibetti S.

Jets at all Scales (eds. G. E. Romero, R. A. Sunyaev & T. Belloni), *Proceedings of IAU*, **275**, 145 (2010)

5. SED fitting of nearby galaxies in the *Herschel* Reference Survey

Ciesla L., Boselli A., Buat V., Cortese L., Auld R., Baes M., Bendo G. J., Bianchi S., Bock J., Bomans D. J., Bradford M., Castro-Rodriguez N., Chanial P., Charlot S., Clemens M., Clements D., Corbell E., Cooray A., Cormie D., Dariush A., Davies J., De Looze I., di Serego Alighieri S., Dwek E., Eales S., Elbaz D., Fadda D., Fritz J., Galametz M., Galliano F., Garcia-Appadoo D. A., Gavazzi G., Gear W., Giovannardi C., Glenn J., Gomez H., Griffin M., Grossi M., Honig S., Hughes T. M., Hunt L., Isaak K., Jones A., Levenson L., Lu N., Madden S. C., O'Halloran B., Okumura K., Oliver S., Page M., Panuzzo P., Papageorgiou A., Parkin T., Perez-Fournon I., Pierini D., Pohlen M., Rangwala N., Rigby E., Roussel H., Rykala A., Sabatini S., Sacchi N., Sauvage M., Schulz B., Schirm M., Smith M. W. L., Spinoglio L., Stevens J., Sundar S., Symeonidis M., Trichas M., Vaccari M., Verstappen J., Vigroux L., Vlahakis C., Wilson C., Wozniak H., Wright G., Xilouris E. M., Zeilinger W., Zibetti S.

SF2A-2010: Proceedings of the Annual meeting of the French Society of Astronomy, Astrophysics (eds. S. Boissier, M. Heydari-Malayeri, R. Samadi & D. Valls-Gabaud), 31 (2010)

6. The Complex Interplay of Dust and Star Light in Spiral Galaxy Discs

Baes M., Gadotti D., Verstappen J., De Looze I., Fritz J., Vidal Pérez E., Stalevski M.

Galaxies and their Masks (eds. D. L. Block, K. C. Freeman & I. Puerari), Springer (ISBN 9781441973160), 187 (2010)

