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THE INFRARED VIEW OF THE UNIVERSE

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Abstract. In this paper we will highlight some observational results that have advanced our knowledge of the infrared properties of star-forming galaxies in the nearby Universe, and will present state of the art modelling tools for the quantitative interpretation of these observations. Prospects for future development in the field will also be discussed.

Key words: infrared astronomy, galaxies: spiral, ISM dust, extinction.

1. INTRODUCTION

Traditionally, our major observational tool in addressing the mystery of the formation and evolution of galaxies has been the observation of starlight in the optical regime. But there is a fundamental complication here – because the fusion reactions that produce the stellar photons also produce refractory elements. And this lead to the presence of dust grains in galaxies, which in turn obscure the stellar light. This complicates the interpretation of measurements of star light and, in extreme cases, may cause galaxies to be undetectable in the optical. At the same time the presence of dust gives a completely new perspective to our understanding of the Universe, since the stellar light that was obscured by dust grains re-appears in the infrared (principally in the Far-Infrared (FIR), that is at rest frame wavelengths between 60–300 μm). Observations of this FIR regime provides a direct probe of the structure of the interstellar medium in galaxies because dust grains are part of the interstellar medium, and more important still, dust grains probe the radiation fields in all parts of the interstellar medium of galaxies. In general, one can identify two main reasons for viewing the Universe in the infrared. The first is that from all of the light emitted by stars in the Universe since the Big Bang, fifty percent is absorbed by dust grains and is re-emitted in the infrared. The second reason is that some of the most fundamental astrophysical processes – star-formation and planet formation – are actually occurring in highly obscured gas clouds, mainly accessible in the FIR/submm regime. And there is a fundamental physical reason for this – that interstellar clouds cannot collapse to the densities needed to form the stars we see today (except perhaps for the first generation of stars in the Universe) without the cooling of the interstellar medium through dust grains.

Knowledge of the infrared emission from star forming galaxies has been revolutionised by the cryogenic cooled orbiting telescopes, like the IRAS, the Infrared Space Observatory (ISO), and the Spitzer Space Telescope and will continue to be strongly advanced through upcoming facilities like the Herschel Space Observatory and in the future by the next generation infrared observatory SPICA (Space Telescope for Cosmology and Astrophysics). Together with the upcoming submm facilities, like SUBA2 on the James Clerk Maxwell Telescope and the Atacama Large Millimetre Array, all these powerful instruments will allow one of the big questions in modern astrophysics to be answered: what is the rate of conversion of gas into stars over cosmic time? – how can this be quantitatively related to physical processes in and around galaxies. More specifically we will be able to understand what are the star formation rates, both within individual galaxies and averaged per unit comoving volume as a function of cosmic epoch; how is the gas chemically enriched, and how much is recycled to the intergalactic medium; what is the role of dust physics in all these processes.

In the following we will give examples of some of the observational results that have advanced our knowledge of dust emission in nearby galaxies and how these can be interpreted in terms of theoretical modelling.

2. THE SPATIAL DISTRIBUTION OF DUST EMISSION IN NEARBY GALAXIES

The ISOPHOT instrument on board ISO was the first instrument that imaged nearby galaxies in the 60 to 200 μm range, with sufficient linear resolution to be able to easily distinguish between the main morphological components in the FIR - nucleus, spiral arms and underlying disk (Haas *et al.* 1998, Hippelein *et al.* 2003, Tuffs & Gabriel 2003). The main discovery was the existence of large amounts of cold dust. This dust was too cold to have been seen by IRAS. The cold dust is associated both with the spiral arms and with the underlying disk. In fact, in all cases most of the emission at 170 μm arises from the underlying disk, which has a completely diffuse appearance.

At shorter infrared wavelengths the spiral arm and the nucleus become more prominent. This is because the warm dust emission component arises predominantly from star-forming complexes in the spiral arms and from the nuclear region. For M33, Hippelein *et al.* (2003) showed that there is a strong resemblance between the morphology of the localised warm dust component at 60 μm and the morphology of the Hα emission, indicating that the 60 μm localised emission traces the star-formation complexes.

The scalelength of the FIR emission increases with increasing FIR wavelength. This implies that the bulk of the 200 μm emission arises from grains heated by a radially decreasing radiation field, as would be expected for grains in the diffuse disk. If most of the 200 μm emission had arisen from localised sources associated with the parent molecular clouds, there should be no FIR colour gradient in the galaxy, since the SEDs of sources which are locally heated should not depend strongly on position.

It was shown that the observed scalelength at 200 μm is comparable to or exceeds the observed scalelength of the optical emission (Alton *et al.*1998, Davies *et al.* 1999). This result implies that the *intrinsic* scalelength of the dust in galaxies is greater than that of the stars. This is because the apparent scalelength of stars should increase with increasing disk opacity (since the inner disk is expected to be more opaque than the outer disk) whereas the apparent scalelength of the dust emission will be less than the intrinsic scalelength (due to the decrease in grain temperature with increasing galactocentric radius). The reason for the difference between the intrinsic scalelength of stars and dust in galaxies is not self-evident, since it is the stars themselves which are thought to be the sources of interstellar grains (produced either in the winds of evolved intermediate mass stars or perhaps in supernovae). One might speculate either that there is a mechanism to transport grains from the inner disk to the outer disk, or that the typical lifetimes of grains against destruction by shocks is longer in the outer disk than it is in the inner disk.

While these studies showed that the scalelength of the 200 μm emission was comparable to or slightly larger than that of the optical emission, they did not actually detect grain emission beyond the edge of the optical disk. Since spiral galaxies in the local universe are commonly observed to be embedded in extended disks of neutral hydrogen – the so called “extended HI disks”, it is a natural question to ask whether these gaseous disks contain grains. This question was answered in the affirmative by Popescu & Tuffs (2003), through dedicated deep FIR maps of a large field encompassing the entire HI disk of the edge-on spiral galaxy NGC891, made using ISOPHOT at 170 and 200 μm (see Fig. 1).

The large amounts of grains found in the extended HI disk of NGC891 (gas-to-dust ratio of ~1%) clearly shows that this gaseous disk is not primordial, left over from the epoch of galaxy formation. It was suggested that the detected grains could have either been transported from the optical disk (*via* the halo, using mechanisms such as those proposed by Ferrara *et al.* 1991, Davies *et al.* 1998, Popescu *et al.* 2000a or through the action of macro turbulence) or that they could have been produced outside the galaxy (for example transferred in interactions with other galaxies). It is interesting to note that, although the dust emission is seen towards the HI component, the grains may not actually be embedded in the neutral ISM. Instead, this dust could trace an “unseen” molecular component, as proposed by Pfenniger & Combes (1994), Pfenniger, Combes & Martinet (1994), Gerhard & Silk (1996), and Valentijn *et al.* (1999). This cold molecular gas component has

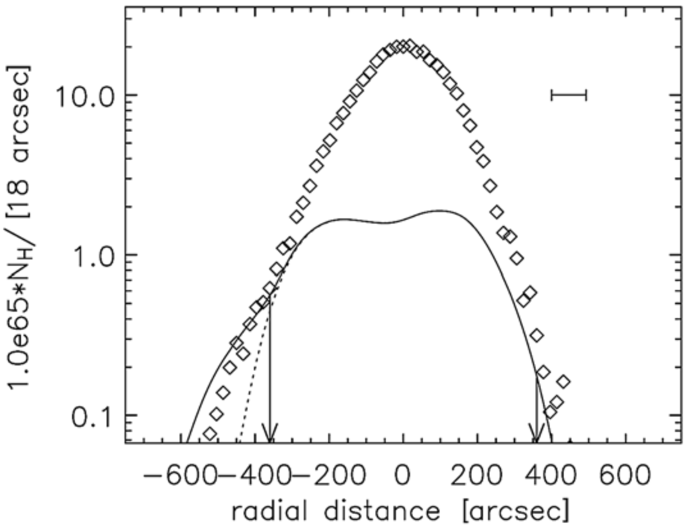

Fig. 1 – The radial profiles of HI emission (from Swaters *et al.* 1997) convolved with the ISOPHOT PSF (solid line) and of 200 μm FIR emission (symbols) of NGC891 (Popescu & Tuffs 2003). Note that the extent and asymmetry of the 200 μm emission follow that of the HI emission. The profiles are sampled at intervals of 18". The negative radii correspond to the southern side of the galaxy and the galaxy was scanned at 60 degrees with respect to the major axis. The units of the FIR profile are W/Hz/pixel, multiplied by a factor of 2×10^{-22} and the error bars are smaller than the symbols. The horizontal bar delineates the FWHM of the ISOPHOT PSF of 93". The vertical arrows indicate the maximum extent of the optically emitting disk. The dotted line represents a modified HI profile obtained in the southern side from the original one by cutting off its emission at the edge of the optical disk and by convolving it with the ISOPHOT PSF.

been invoked as a dark matter component to explain the flat rotation curves of spiral galaxies. Its presence might also reconcile the apparent discrepancy between the very low metallicities measured in HII regions in the outer disk (Ferguson, Gallagher & Wyse 1998) and the high ratio of dust to gas (on the assumption that all gas is in form of HI) found by Popescu & Tuffs (2003) in the extended HI disk of NGC891.

There is some evidence that this phenomenon, of dust extending beyond the optical disk and associated with extended HI disks, is not confined to spiral galaxies. Observations of dwarf galaxies in the Virgo Cluster (Tuffs *et al.* 2002) showed that in two cases the extent of the 170 μm emission exceeded that of the optical emission (Popescu *et al.* 2002) and coincided with the extended HI envelopes. The main observational difference between the giant spiral and the dwarfs may be that for the dwarfs the integrated 170 μm emission is dominated by the extended emission component external to the main optical body of the galaxy, whereas for the giant spirals the long-wavelength emission predominantly arises from within the confines of the optical disk of the galaxy.

Having established the extent and morphology of the cold dust, it is important to measure the fraction of light from young stars which is re-radiated by this dust, since it is these stars which are mainly heating the dust. This fraction can be investigated not only globally, but as a function of position in the galaxy. This has been done by a direct comparison of ISOPHOT maps at 60, 100 and 170 μm with UV maps obtained with GALEX (Galaxy Evolution Explorer) for the case of M101 (Popescu *et al.* 2005). The trend for the FIR/UV ratio to be higher in the diffuse interarm regions than in the spiral-arms is seen in Fig. 2. This apparently surprising result was explained in terms of the escape probability of UV photons from spiral arms and their subsequent scattering in the interarm regions, and in terms of the larger relative contribution of optical photons to the heating of the dust in the interarm regions. The combined effect of the optical heating and the

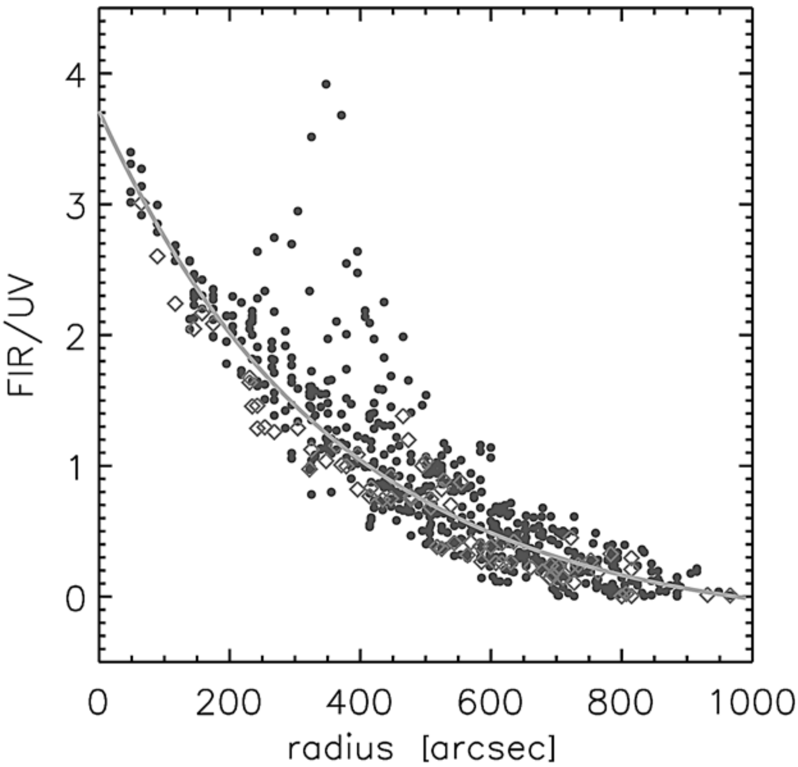

Fig. 2 – The pixel values of the FIR/UV ratio map of M101 (Popescu *et al.* 2005) at the resolution of the 170 μm image versus angular radius. The dots are towards lines of sight towards interarm regions and the diamonds towards the spiral arm regions. The solid line is an offset exponential fit to the data.

scattering of the UV emission means that the FIR/UV ratio will not be a good indicator of extinction in the interarm region.

Despite these local variations, the main result of Popescu *et al.* (2005) is the discovery of a tight dependence of the FIR/UV ratio on radius, with values monotonically decreasing from ~ 4 in the nuclear region to nearly zero towards the edge of the optical disk (see Fig. 2). This was interpreted in terms of the presence of a large-scale distribution of diffuse dust having a face-on optical depth which decreases with radius and which dominates over the more localised variations in opacity between the arm and interarm regions.

3. THE INTEGRATED PROPERTIES OF DUST EMISSION IN NEARBY GALAXIES

The first investigation of the integrated dust emission properties across the Hubble sequence of galaxies has been achieved by Popescu *et al.* (2002). This study was based on the FIR observations (Tuffs *et al.* 2002) of a complete and optical selected sample of galaxies in the Virgo Cluster (The ISOPHOT Virgo Cluster Deep Survey; IVCDS). The IVCDS provides a database for statistical investigations of the FIR SEDs of gas-rich galaxies in the local universe spanning a broad range in star-formation activity and morphological types, including dwarf systems and galaxies with rather quiescent star-formation activity. The main result of this survey was the universality of the cold dust component, which was shown to be present within all types of spirals. It also showed that almost all galaxies have both warm and cold dust emission components.

The cold dust component is most prominent in the most "quiescent" galaxies, where the cold dust temperatures were found to be broadly distributed, with a median of 18 K (Popescu *et al.* 2002), some 8–10 K lower than would have been predicted by IRAS. The corresponding dust masses were correspondingly found to be increased by factors of typically 6–13 (Popescu *et al.* 2002), with respect to previous IRAS determinations. As a consequence, the derived gas-to-dust ratios are much closer to the canonical value of ~160 for the Milky Way, but with a broad distribution of values (Popescu *et al.* 2002). Furthermore, the cold dust component provides not only the bulk of the dust masses, but even the bulk of the FIR luminosity, in particular for the case of the most quiescent spirals. This would also imply that most of the luminosity is carried by the diffuse cold dust. Another result to come out from this survey is that the mean percentage of stellar light re-radiated by dust is ~30% (Popescu & Tuffs 2002) and that there is an increase of the ratio of the dust emission to the total stellar emitted output along the Hubble sequence, ranging from typical values of ~15% for early spirals to up to ~50% for some late spirals.

4. MODELLING THE INFRARED EMISSION FROM GALAXIES

It is clear that these many and varied observational studies of star-forming galaxies in the far-IR have the potential to provide completely new insights into the properties of the interstellar medium of galaxies, and the stars which have formed out of this medium, both today and in the past. However, to realise this potential, intrinsic physical properties of galaxies must be extracted from the observed images and integrated SEDs, requiring a quantitative understanding of the effect of dust in attenuating the light from different stellar populations and how the absorbed stellar light is re-emitted by the dust in the infrared. This can be achieved by modelling the whole spectral energy distribution (SED) of galaxies, from the UV/optical to the Far-IR/submm. Such a modelling tools has been introduced by Popescu *et al.* (2000b) and further developed in a series of papers by Misiriotis *et al.* (2001), Tuffs *et al.* (2004), Möllenhoff, Popescu & Tuffs (2006). This is the only self-consistent model thus far which has proved capable of simultaneously predicting the observed optical/FIR SEDs (Popescu *et al.* 2000b), the morphologies (Popescu *et al.* 2004) of galaxies both in the stellar light and in the dust emission, and the attenuation-inclination relation (Driver *et al.* 2007) of large statistical samples like the Millennium Galaxy Catalogue sample (Liske *et al.* 2003).

There are several essential elements to the calculation of dust emission, which drive the design of the algorithm and its implementation in an SED modelling tool. Firstly, one needs to specify the relative positions of stars and dust. For the stellar populations seen through more optically thin lines of sight this is derived by fitting the optical and near-infrared images of galaxies. One expected feature will be the reproduction of a thin star-forming layer in galaxian disks, as seen in the molecular layer in the Milky Way, which has a scale height of just 90\,pc and it is crucial for the calculation of dust emission. Failure to handle this complexity will lead to problems when confronting the simulations with data: for example, although they used elements of the model of Popescu *et al.*, Dasyra *et al.* (2005) did not incorporate dust associated with the young stellar population in the thin molecular layer and their solution fails to predict the observed attenuation – inclination curves. For similar reasons the models of Xilouris *et al.* (1998, 1999, 2000) and Bianchi *et al.* (2007), although successfully reproducing the optical appearance of galaxies, have difficulties accounting for the observed FIR SEDs and attenuation-inclination curves. Secondly, once a description of the geometrical distributions of dust and stellar emissivity is available, one needs to calculate the radiation densities throughout the dust-bearing volume of the galaxy. Since at UV and short optical wavelengths the scattering probability is larger than the absorption probability, and is highly anisotropic, this requires a radiation transfer calculation incorporating anisotropic scattering. The method of scattered intensities which is used (Kylafis & Xilouris 2005) is particularly suited to the calculation of energy densities, having clear advantages in this respect over Monte Carlo calculations. Another important aspect of the code of Popescu *et al.* is its ability to calculate the variation of colour of the radiation field from point to point in the galaxy, a feature missing from semi-analytic models for calculating dust emission SEDs, such as the models by Draine & Li (2007), which assume a fixed colour (that of the radiation field in the solar neighbourhood) at all positions and in all objects.

Lastly, one of the largest but completely unavoidable complexities of these calculations is that most of the dust grains, especially the smaller ones, do not emit in equilibrium with the radiation fields, but are stochastically heated. Thus, a probability distribution of temperature for grains of all sizes needs to be computed at all points of the galaxy, according to the local intensity and colour of the interstellar radiation fields. This treatment is crucial for predicting the ratio between the MIR and FIR emission in galaxies, and in general for accounting for the observed infrared colours. In addition, the PAH molecules are only stochastically heated, therefore any prediction of PAH emission cannot be made without the ability to compute non-equilibrium radiation processes. The ray-tracing method used in the radiative transfer code of Popescu *et al.* is ideal for calculating these processes and this code has been optimised to produce high speed computations of the stochastic emission. We should mention that because of the complexity of these calculations and the large computational time requested, most of the available radiative transfer codes (SKIRT – Baes *et al.* 2005; SUNRISE – Jonsson 2006) do not include this fundamental process.

5. FUTURE MODELLING DEVELOPMENTS

The rapid advance in computational power makes it possible now to merge the SED modelling tool with the models for galaxy formation and evolution. This will allow the determination of the evolution of the IR/submm dust and gas emission signatures corresponding to the conversion of gas into stars in evolving galaxies as predicted in current theories of structure evolution in the universe. The predictions of these calculations, when compared with data, will directly constrain theories for the formation and evolution of galaxies, since they will incorporate all known physics related to sources and sinks of grains in galaxies and in the surrounding IGM, as well as to the cooling and heating mechanisms involving grains. This would be needed to compare data expected from upcoming surveys of dust emission from distant galaxies with SCUBA2, Herschel, JWST, Planck with realistic model predictions. Apart for this, these simulations will be crucial for interpretation of data from the wide-field deep optical and near-IR surveys being executed or planned, like VISTA and UKIDS.

Here we give some examples of applications of these simulations:

i) Once applied to statistically significant numbers of simulated galaxies, these calculations will provide predictions for the evolution of the IR luminosity functions (LF) in key bands – PAH, MIR, FIR, submm – which will for the first time allow the knowledge of these LFs as derived from Spitzer (*e.g.* Babbedge *et al.* 2006) and Herschel observations to provide an entirely complementary test of models for structure formation. This will be the preferred method of testing ideas of structure formation at high redshift, where most of the emergent energy is in the form of FIR emission (both for isolated and merging systems).

ii) By the same token they will be able to provide accurate predictions for dust-attenuated LFs in the UV and optical bands. This is particularly crucial for LFs in the rest frame UV where the large majority of light is absorbed and re-radiated by dust and where previous correction have been very crude, essentially involving foreground screens which take no account of the different geometrical relations between dust and stellar populations of different ages.

iii) These calculations will yield predictions for the SED of the accretion-powered component of the emergent dust emission from heavily obscured AGN as a function of basic quantities such as the mass of the central black hole and the efficiency of mechanical feedback from the AGN (as predicted in the smooth particle hydrodynamical simulations). Comparison of these predicted SEDs with SEDs measured by Spitzer and Herschel, will place constraints on these quantities, and in general on the relative importance of AGN and starburst activity in powering the infrared emission in merging systems, especially when the infrared data is considered in conjunction with direct probe in X-rays of the AGN in favourably orientated systems.

iv) Using the self-consistent calculation of the cooling line emission from the diffuse neutral ISM this model will predict quite precisely the relation of the diffuse interstellar dust and PAH emission to the emission in the [CII] 158 micron line (thought to be the principal coolant of the neutral ISM) and the [OI] 63 micron line.

Comparison of these predictions with the expected flood of high quality observations of the FIR cooling lines with Herschel will provide a critical test of standard theories of the heating and cooling of interstellar gas in galaxies, for galaxies of all types (dwarfs spirals and starbursts) in the local universe and for high luminosity galaxies out to redshift of ca. 3. Because the photoelectric heating is a strong function of the hardness of the UV light, the [CII] and [OI] lines will be very sensitive to the IMF of the stellar populations and so will provide a fundamentally new constraint on the steepness and uppermass cut-off of the IMF and thus on the injection rate of metals in the ISM.

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