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Dust emission and scattering in dense interstellar clouds

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ABSTRACT

Dust has a crucial role in the physics of interstellar medium (ISM) and it is one of the main tracers used in studies of dense clouds. Its importance has been accentuated by the large amounts of data available from the recent fleet of infrared and submillimetre satellites. These observations are providing further insights into the properties of interstellar dust grains and the changes they undergo during the star formation process.

We examine some of the evidence for dust evolution coming from submillimetre dust emission and from light scattering at near-infrared and mid-infrared wavelengths. Planck and Herschel satellite observations have covered the peak of large grain emission, enabling studies of large cloud areas with unprecedented sensitivity and detail. The data are confirming results from earlier studies where changes of submillimetre dust opacity and spectral index were first reported. The changes are connected to dust evolution and growth as dust moves from diffuse ISM to molecular clouds and into pre-stellar clumps. Corroborating evidence on dust growth has been obtained recently from mid-infrared where enhanced scattering, the 'coreshine' phenomenon, is attributed to the growth of up to micron-sized dust particles.

We will summarise results of previous infrared and submillimetre studies. We will describe ongoing work on Herschel data, done partly in the context of the programme *Galactic Cold Cores* (GCC). We will also discuss recent results from the Spitzer project *Hunting coreshine*, where the mid-infrared scattering is investigated in a partly related sample. We will also touch on some of the problems and modelling challenges encountered in these studies.

1. Introduction

With dense interstellar clouds we refer to molecular clouds and especially their high density regions that are directly involved in star formation. Molecular clouds have a wide range of sizes, from giant molecular clouds down to ~ 1 pc sized globules. For molecular gas to survive, it needs to be shielded from interstellar radiation field by at least $A_V \sim 1$ mag of dust extinction. Molecular gas is associated with gas densities above $n_H > 10^2$ cm^{-3} and gas temperatures $\sim$10–20 K (Bergin and Tafalla, 2007). However, even gravitationally unbound clouds have significant structure down to the smallest observable scales. This applies not only to density but also to temperature, velocity, and chemical composition. Clouds contain denser clumps with sizes of the order of 1 pc, and cores, with sizes a fraction of one parsec. These have densities orders of magnitude higher than the average cloud density and temperatures close to or even below 10 K. The conditions are thus very different from those in diffuse clouds, and are suitable for grain growth resulting from freeze-out of gas molecules and aggregation of dust particles. The cores are further divided to starless and prestellar cores, depending on whether they are gravitationally bound and thus likely to collapse and form stars (Andre et al., 2000; Mckee and Ostriker, 2007). Star formation itself has a drastic effect on dust via heating and shocks. However, we will concentrate on the evolution before the onset of star formation.

Through extinction, thermal emission, and scattering, dust is an important tracer of the structure and physical state of dense clouds. This role has become even more important thanks to many infrared satellites (e.g., ISO, Spitzer, AKARI) and especially by the submillimetre observations made by the Planck (Tauber et al., 2010) and Herschel (Pilbratt et al., 2010) satellites. Dust plays furthermore an important role in the physics of clouds. On the surface of molecular clouds, photoelectric heating, extraction of electrons from small grains by UV photons, is the main source of gas heating (e.g. Bakes and Tielens, 1994; Wolfire et al., 2003). Deeper in the clouds, UV and optical photons become absorbed by dust and gas temperatures are reduced to $\sim$10–20 K (Crapsi et al., 2007; Juvela and Ysard, 2011). The dust temperature drops even faster and, once the density exceeds $n \sim 10^5$ cm^{-3}, gas and dust become thermally coupled. As a result, the lowest gas temperatures measured in prestellar cores are $\sim$6–7 K (Pagani et al., 2007; Harju et al., 2008). Dust affects gas temperature also indirectly, through gas phase abundances. Many molecules, most notably H_2, are formed on dust grains while, conversely, in cold cloud cores most molecular species freeze onto dust grains, thus reducing the efficiency of line cooling. Although

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dust is small component by mass, detailed knowledge of its properties is important for our understanding of the ISM and the star formation process.

The wide range of densities and temperatures and the interactions with gas imply changes in dust characteristics. The effects should be most pronounced in the densest cores. Many of the methods traditionally used to infer dust properties, such as extinction, polarisation, and scattering at UV and optical wavelengths (see Draine, 2003), are made difficult by the high optical depths. Some information on the smallest grains can be obtained via their mid-infrared emission bands (e.g. Desert et al., 1990; Draine and Li, 2007; Compiègne et al., 2011) and, similarly, infrared absorption features provide quantitative data on ice mantle (e.g. Whittet et al., 1996, 2013; van Dishoeck, 2004; Öberg et al., 2011; van Dishoeck et al., 2013). However, we concentrate on evidence provided by dust emission at submillimetre and millimetre wavelengths and, on the other hand, light scattering at near-infrared (NIR) and mid-infrared (MIR) wavelengths.

In the following, we will refer especially to results of the *Galactic Cold Cores* project that has carried out Herschel observations of 116 fields where the Planck satellite survey had already located compact sources characterised by cold ($T < 14$ K) dust emission (Planck Collaboration et al., 2011b,c; Juvela et al., 2012). In studies of MIR scattering, most data come from Spitzer satellite, especially the project *Hunting Coreshine* (PI R. Paladini; see e.g., Lefèvre et al., 2014).

2. Long wavelength dust emission

At far-infrared and longer wavelengths, dust emission spectrum is often described with a modified black body law,

$$I_\nu = B_\nu(T)(1-e^{-\kappa_\nu \times \Sigma}) \approx B_\nu(T) \times \kappa_\nu \times \Sigma \propto B_\nu(T)\nu^\beta. \quad (1)$$

Here κ_ν is dust absorption coefficient at frequency ν and, depending on the units of κ_ν, Σ can be column density or surface density of dust or the sum of gas and dust. Under the assumption that dust opacity follows a powerlaw, parameter β is a constant spectral index, $\kappa_\nu \propto \nu^\beta$. With observations at three or more wavelengths, this simple model can be used to determine both T and β.

The equation contains a number of assumptions. It assumes a single temperature for all dust particles within the beam. Temperature T can be called colour temperature, to separate it from the physical dust temperature, making it an empirical parameter that merely describes the shape of the observed spectrum. However, if the source is not isothermal, the emission does not precisely follow any single modified blackbody. This means that only wavelengths beyond ~ 100 μm should be used, to avoid significant contribution from stochastically heated small grains with a wide temperature distribution. Nevertheless, some temperature variations do always exist. These cause uncertainty in the physical interpretation of the fitted parameters and also mean that the values of T and β will depend on the actual frequencies used (e.g. Shetty et al., 2009b; Malinen et al., 2011; Juvela and Ysard, 2012b).

The equation also assumes that the spectral index β is constant within the beam and over the observed wavelengths. Variations of β have been observed as a function of Galactic location and between diffuse medium, molecular clouds, and dense clumps (e.g. Dupac et al., 2003; Désert et al., 2008; Planck Collaboration Int. XIV, 2014; Planck Collaboration XI, 2014). There is growing evidence of differences between FIR and millimetre wavelengths. This has been observed in laboratory (Agladze et al., 1996; Mennella et al., 1998; Boudet et al., 2005; Coupeaud et al., 2011) and recently also in astronomical studies (Gordon et al., 2010; Paradis et al., 2011; Planck Collaboration Int. XVII, 2014; Paradis et al., 2014; Juvela et al., 2015a).

Finally, the explicit approximation written out in Eq. (1) indicates that the emission is assumed to be optically thin, making the determination of temperature and spectral index independent of column density. This is generally true although the optically thick limit can certainly be reached at small scales towards protostellar cores. At 100 μm the emission becomes optically thick already for column densities a few times $N(H_2) = 10^{23}$ cm^{-2}, a value that is approached, for example, in some infrared dark clouds (Kainulainen and Tan, 2013). If the optical depth is not insignificant, it is not enough to avoid the approximation in Eq. (1) because emission observed at different wavelengths is now originating in completely different regions. However, this is already partly true because of temperature variations.

In the case of clouds that are optically thick for the radiation heating the grains (UV, optical, and NIR wavelengths), the modified blackbody law should be considered only as a first step in the analysis. If there is enough good quality data, the line-of-sight temperature variations can be taken partly into account by fitting multiple temperature components, possibly even with different values of the spectral index as done in Planck Collaboration Int. XVII (2014) and Planck Collaboration Int. XIV (2014) (see also Draine and Li, 2007; Compiègne et al., 2011). However, at high optical depths, one needs to resort to radiative transfer methods (e.g. Steinacker et al., 2013) to estimate physically motivated temperature variations. Unfortunately even detailed modelling does not guarantee accurate results, because the line-of-sight structure of the clouds and details of the local heating remain poorly constrained (Juvela et al., 2013).

2.1. Dust opacity

Dust opacity relative to the total amount of dust or gas has been investigated with observations in far-infrared, sub-millimetre, and millimetre regimes, with ground based telescopes, satellites (IRAS, COBE, ISO, etc.), and balloon-borne telescopes. In diffuse clouds, the dust opacity can be compared directly with hydrogen column density. In molecular clouds, absolute measurements of column density are more difficult and emission must be examined, for example, relative to NIR extinction or the total gas mass traced by γ rays (Planck and Fermi Collaborations, 2014). Because of the complex effects of line-of-sight temperature variations, modelling is needed when the relative opacity of different FIR and submm bands is examined. Modelling can also provide an indirect handle on grain properties. The low dust temperatures of molecular clouds are difficult to explain based on the attenuation of the interstellar radiation field (ISRF) alone (Laureijs et al., 1991; Abergel et al., 1994, 1996). In many cases the data imply a significant increase of the long wavelength (FIR, submillimetre) emissivity with values 2–4 times higher than in diffuse medium (Stepnik et al., 2003; Kramer et al., 2003; Bianchi et al., 2003; del Burgo et al., 2003; Kiss et al., 2006; Ridderstad et al., 2006; Lehtinen et al., 2007). Theoretical calculations of dust aggregates have predicted clear changes of long wavelength emissivity (e.g. Wright, 1987; Mathis and Whiffen, 1989; Bazell and Dwek, 1990; Ossenkopf, 1993; Ossenkopf and Henning, 1994; Stognienko et al., 1995; Ormel et al., 2011; Köhler et al., 2011, 2012). For example, in their analysis of *Herschel* data on the L1506 filament in Taurus, Ysard et al. (2013) characterised the dust evolution as a function of density. In the outer filament layers the emission was found to be consistent with grain properties of diffuse clouds, but the emissivity was found to increase by a factor of ~ 2 above gas densities of a few times 10^3 cm^{-3}. The change was attributed to the formation of fluffy aggregates. The grain coagulation process itself has been addressed by several observational and theoretical studies (e.g. Dominik and Tielens, 1997; Bernard et al., 1999; Cambrésy et al., 2001; Stepnik et al., 2003; Ormel et al., 2009; Hirashita and Li, 2013).

Planck Collaboration et al. (2011a) found a factor of two increase in 250 μm opacity σ(250 μm) already between atomic and molecular clouds. In Vela molecular clouds, Martin et al. (2012) used BLAST observations to derive at 250 μm values $(2–4) \times 10^{-25}$ cm^2 H^{-1}, 2–4 times the numbers found in diffuse, high latitude regions. From Herschel observations of the Orion A molecular cloud Roy et al. (2013)