DUST EVOLUTION IN THE COLD AND DIFFUSE INTERSTELLAR MEDIUM: THE HERSCHEL PERSPECTIVE

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Abstract

The PACS and SPIRE instruments of Herschel combine the sensitivity, the spectral coverage, the angular resolution and the mapping efficiency to provide a full picture, of the evolution of large dust grains from cirrus to dense cores. This evolution is though to result from accretion, coagulation and fragmentation processes, that depends on the density structure of the ISM, the amplitude of the turbulent motions and the excitation conditions. The far-infrared and sub-millimeter emission maps provided by Herschel will allow us 1) to characterize the structure of the interstellar medium, 2) to study the evolution of dust and its relation with the gas phase properties and 3) it will also provide important informations on the statistical properties of the dust emission which are crucial for the detection of proto-stellar cores and for the study of extra-galactic emission. Such maps will also be a key input to the components separation for Planck. The combination of Herschel observations with IRAS, ISO, SIRTF and ASTRO-F data will reveal the whole spectral energy distribution (SED) of dust and will allow to characterize the complete dust size distribution and study the dust-gas relation.

Key words: interstellar medium; infrared; dust; turbulence; Herschel

1. Interstellar dust in the ISM

Interstellar dust plays a key role in the thermodynamical and chemical evolution of the interstellar medium (ISM). Dust grains control the heating rate of the gas via the photo-electric effect (Bakes & Tielens, 1994) and also the formation rate of the H_2 molecule that arises at their surface (Duley & Williams, 1993). Therefore, the emission spectrum of dust is a tracor of the grain properties but also of the physical conditions of the ISM.

In the solar neighbourhood, Boulanger & Pérault (1988) and Boulanger et al. (1996) have showed that dust and gas are well mixed at large scale (7°), and that, in diffuse clouds far from star forming regions, dust is uniformely heated by the interstellar radiation field (ISRF). The large grains, which are in thermal equilibrium with the radiation field, are responsible for a 17.5 K grey body (spectral emissivity index of 2) in the far-infrared (see Fig. 1). At shorter wavelength, the exces emission from the grey body is due to smaller grains stochastically heated by the stellar radiation.

Several studies have also shown that the spectral energy distribution (SED) of the dust emission is modified from place to place in the cold neutral interstellar medium (CISM), even at very small scales (e.g. Boulanger et al. (1990) and Abergel et al. (1994)). One example is shown in Fig. 2 where the 100 μm IRAS map of the Polaris cirrus is shown on the left side and the variations of the 60 μm emission with respect to the 100 μm emission on the right side. This high Galactic latitude cloud is optically thin to the ISRF; the structure observed in this color map reflect changes in the temperature and/or the size distribution of small grains. Submillimeter observations between 200 and 600 μm conducted with the balloon-borne instrument SPM/PRONAOS towards a few cold regions like the one seen in Fig. 2 (e.g. Bernard et al. 1999, Ristorcelli et al. 1998, Stepnik et al. 2001) revealed condensations of cold dust temperature (as low as $\sim$ 12 K). From COBE data, Lagache et al. (1998) have also shown that, on large angular scales ($\sim$1°), the dust temperature in molecular clouds with low star forming activities is systematically

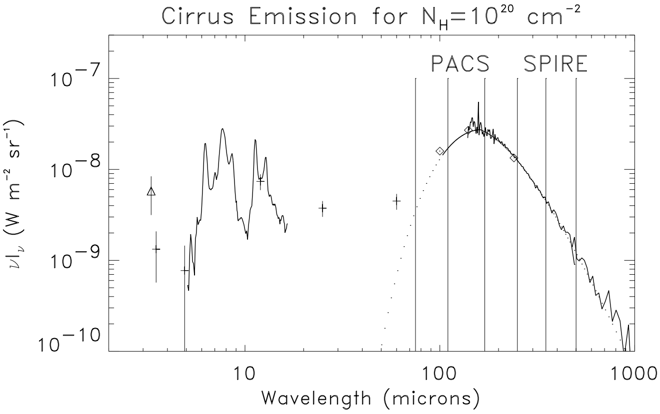

Figure 1. Typical spectral energy distribution of dust for a cirrus of $N_H = 1 \times 10^{20}$ cm^{-2}. This spectrum is a collection of data coming from DIRBE (Bernard et al., 1994), FIRAS (Boulanger et al., 1996), ISO (Boulanger et al., 1996a) and Arome (Giard et al. 1994). The central wavelenght of the three PACS bands and of the three SPIRE bands are also shown.

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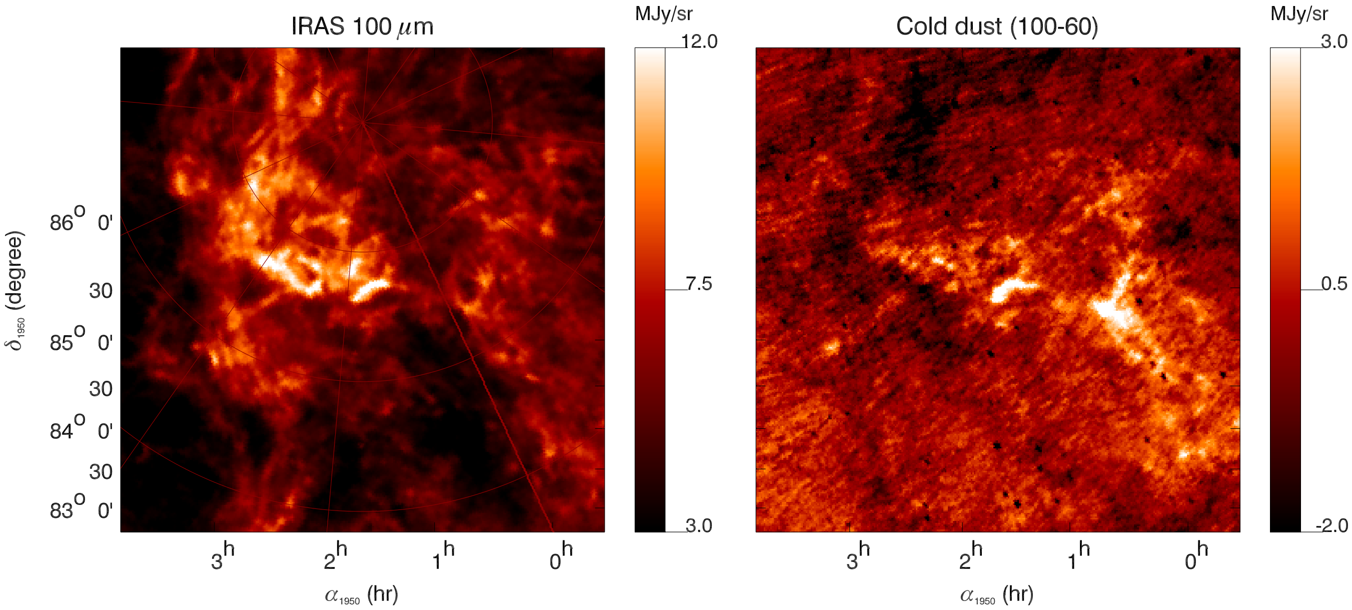

Figure 2. The polaris cirrus cloud. **Left:** *100 μm IRAS map.* **Right:** *Color map of the excess from the linear relation between the 100 and 60 μm bands.*

lower than in the diffuse medium. The modelisation of these observations shows that the cooling of the grains at thermal equilibrium with the radiation field is due to an increase of the submillimeter emissivity, combined with a decrease of the abundance of transiently heated small particles (Stepnik et al. 2001). These two effects are likely due to coagulation of dust grains. How this dust evolution proceeds is still unclear. We do not know how it is related to local physical conditions (e.g. condensation from atomic to molecular gas, the role of turbulence) and on what time scale it occurs.

Turbulence is known to modify and accelerate the effects of coagulation/fragmentation on the dust size distribution and the outcome depends on the relative velocities of the grains as a function of size. If turbulent motions are energetic enough they could fragment grains in collisions leading to the formation of small particles. This possibility has recently received strong support from ISOCAM observations of a cirrus cloud (Miville-Deschênes et al, 2001).

From such studies, the dust properties of the CISM are inferred to be inhomogeneous, with large departures from mean values in localized regions. These spatial variations of the SED are a spectacular manifestation of the evolution of matter in space. They reveal small scale variations of the dust size distribution that could influence the thermodynamical and chemical evolution of the gas and even induce long lasting phase transitions. Therefore, the study of the interplay between dust and gas properties is of prime importance to understand the general evolution of the ISM.

With its sensitivity, spectral coverage and angular resolution, Herschel will be a perfect tool to study the properties of interstellar grains in thermal equilibrium with the radiation field in various interstellar environnements, from diffuse gas to dense cores, allowing the analysis of the whole dust cycle. The wavelength range of Herschel is favorable for the study of the coagulation processes associated with the condensation of the gas. Herschel will allow us to study of the physical processes that regulate the evolution of the larger grains and find where in the ISM and on what spatial and time scales these processes are active. The combination with observations from IRAS, ISO, SIRTF and ASTRO-F will span the whole dust SED. In addition, by combining dust maps with tracers of the gas phase (e.g. HI and CO maps), it will be possible to relate local variations of the dust SED with the gas physical conditions and kinematics.

2. DETERMINATION OF THE DUST PARAMETERS

In the far-infrared (FIR) and sub-millimeter (submm), the SED of the interstellar dust particles (Fig. 1) is often characterized by a grey body curve emitted by large dust grains in thermal equilibrium with the radiation field:

$$I(\lambda) = A \times B_\lambda(T) \times \lambda^{-\beta} \tag{1}$$

with only three parameters: temperature T, emissivity index β and normalisation factor A.

With Herschel we will study the emitting properties of interstellar grains in thermal equilibrium with the radiation field. *A priori* the three parameters characterizing the emission can be determined by only three measurements along the grey body spectrum. But the accuracy of this determination depends greatly on the choice of the wavelengths used. The three bands of SPIRE and the two long wavelengths bands of PACS can be used (the 60-90 μm band is contamited by emission due to stochastically heated dust). To estimate what would be the most favorable observational conditions, we have computed what would be the error on T and β determined from observations done with SPIRE alone, PACS alone, and SPIRE and PACS together (Fig. 3). We have done this computation for $10 < T < 20$ K and $1.5 < \beta < 2.5$, and we assume a 10% error on the PACS and SPIRE flux measurements. We notice that when standard dust (corresponding to the average spectrum in the diffuse medium: T = 17.5 K, β = 2) is observed by SPIRE alone, the errors on the determination of T and β are respectively ∼ 25% and ∼ 5%. In the same conditions PACS is better since the PACS bands cover each side of the grey body peak emission, making it a more adapted instrument to determine the temperature. The error on T drops to ∼ 10%, but the normalisation factor cannot be computed with only two measurements. Finally the strongest constraints are given with the combination of SPIRE and PACS: errors are respectively of ∼ 4% and ∼ 2% are obtained. We conclude that it is necessary to combine FIR and submm data to follow the evolution of large dust grains from diffuse regions (T∼17.5 K) to dense molecular regions (T∼12-14 K). This can be done by the combination of PACS and SPIRE but one has also to consider the information provided by IRAS 100 μm, SIRTF-MIPS 160 μm or the ASTRO-F FIR all-sky survey.

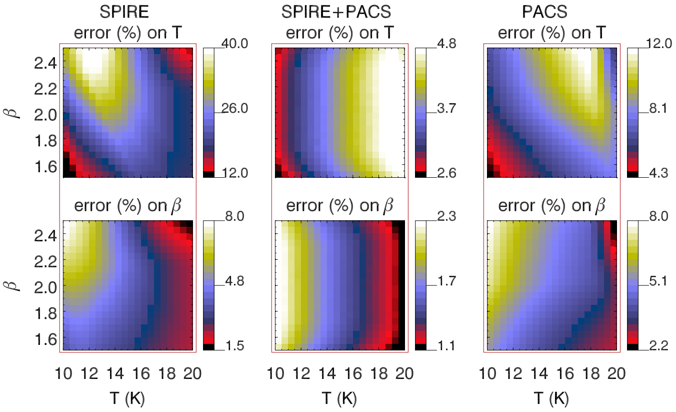

Figure 3. Estimation of the error on the determination of the temperature T (top) and the spectral index β (bottom) for three observational configuration (SPIRE alone, PACS alone or SPIRE and PACS together). The error on T and β has been computed on the basis of a 10% error on the flux measured by SPIRE and PACS.

The spectroscopic mode of PACS and SPIRE will provide a complete description of the dust SED which will complement imaging programs. Spectra on selected lines of sight will allow us to asses to validity of the SED parametrization used for the interpretation of the photometric data and search for possible spectral signature of dust evolution (e.g. ice features). The interpretation of these spectra will be done in relation with laboratory experiments. In addition, such spectra will also provide detections of gas lines which are key diagnostics for the physical conditions of the ISM (e.g. C i, C ii, N ii)

3. Mapping of interstellar dust emission

3.1. Spatial variations of the dust SED

As we have seen in the previous section, the wavelength coverage of PACS and SPIRE is very well adapted for the study of large grains in thermal equilibrium with the radiation field. In addition, the sensitivity and scanning capability of these instruments make it possible to produce maps with high dynamic range in brightness and spatial scales. PACS and SPIRE will also provide significant gain in angular resolution with respect to IRAS, SIRTF and ASTRO-F in the FIR and Planck in the submm. In this, Herschel will open a unique an original perspective on the ISM.

Angular resolution and a high dynamic range in spatial scales is very important for the study of dust evolution. Spatial scales on which variations of the dust emission are observed can be statistically related to the time scales of the physical processes responsible for the modification of the dust properties. The identification of local variations of the dust properties in the ISM and the study of the scales (spatial and temporal) on which these variations occur can only be done by mapping large regions of interstellar clouds. This is illustrated in Fig. 2 where only two very contrasted cold dust structures appear within a 156 square degrees map. Due to turbulent mixing, angular resolution is also critical to sample the time evolution of dust properties. For instance, one can see the impact of angular resolution on dust studies by comparing what has been done on cold dust with DIRBE (40’ resolution - Lagache et al., 1998) and with SPM/PRONAOS (2.5’ - Stepnik et al., 2001). Therefore, mapping large pieces of nearby clouds with Herschel will provide an original perspective on the ISM which will be complementary of what could be done with Planck on larger scales and ALMA at small scales.

The mapping of large regions with spatial redundancy could also be very important for the correction of instrumental effects. For ISOCAM (the camera of ISO), the comparison of the structure of the sky at various spatial scales allowed to correct instrumental effects with various time scales (Miville-Deschênes et al., 2000), and therefore obtain the optimum sensitivity of the instrument. We think that it should be a real concern of the instrumental teams to develop instruments that allow the mapping at all scales.

3.2. STRUCTURE FROM CIRRUS TO DENSE CORES

The FIR and submm emission of large grains observed with PACS and SPIRE will be used to trace the structure of the ISM down to the sub-arcminute scales from the diffuse ISM to dense cores. The study of the dust properties will combine the observations, laboratory experiments and physical modelling of grain properties and radiation transfer. This effort should lead to a good understanding of the relation between the dust opacity and the dust and gas column densities. One of the goals is to produce column density maps out of the Herchel maps. These maps will be used for detailed correlation with gas maps and statistical analysis. These maps will be complementary of those provided by the usual gas tracers (HI and molecules). In particular dust is unique in tracing matter over the transition between atomic and molecular gas and in very dense regions for which the molecular lines are poor tracers due to abundance/depletion effects.

Statistical studies of the infrared sky have been carried out with the IRAS maps (Gautier et al. 1992). At small scales, the brighness fluctuations of the dust emission can depart significantly from a Gaussian distribution (Abergel et al. 1996). This is in particular true for the cold dust component associated with molecular clouds. These fluctuations are a source of confusion for the detection of proto-stellar cores and external galaxies. Therefore, it is important to map large areas to characterize the statistical properties of the dust emission as a function of scale over the full range of sky brightness.

3.3. FOREGROUND FOR PLANCK

The Planck experiment, dedicated to study the fluctuations of the Cosmic Microwave Background (CMB), will observe the whole sky from 350 μm to 10 mm with an angular resolution of $\sim$ 5 arcmin. The interstellar dust emission and extra-galactic backgrounds need to be characterized and removed properly in order to study the CMB at the Planck sensitivity limit. To achieve this goal we have to understand how the emission of these components are related between the various observed wavelengths. For dust, it is clear that this means understanding the evolution of dust emission properties within the diffuse ISM. For the extra-galactic background, one needs to determine the intrinsic spectra of infrared galaxies and their redshift distribution. A survey of a large area at high Galactic latitude over a range of cirrus brightness will be of great help for modelling the Galactic and extra-galactic components.

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