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INTERSTELLAR DUST ON THE EVE OF HERSCHEL AND PLANCK

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Abstract. In this contribution I review some of the key scientific questions that animate the interstellar dust community a few months before the launch of Herschel and Planck. Great progress have been made in the past 25 years on the subject of interstellar dust using infrared observations from space. With the advent of sub-millimeter and millimeter observations with Herschel and Planck, new scientific challenges are coming and exciting discoveries are to be expected. In particular Herschel and Planck will bring key information 1) on the growth process of dust grains, the first step toward the formation of planetesimals, 2) on the structure of the interstellar medium and its link with interstellar turbulence, 3) on the physical conditions of the Galactic halo clouds which are thought to have some cold dust, 4) on the properties of the interstellar magnetic field and 5) on the interstellar PAHs using their spinning dust emission in the millimeter.

1 Introduction

Even though interstellar dust weights less than one percent of the whole interstellar matter it plays an important role in the physics of the interstellar medium (ISM). Dust grains act as catalysis for chemical reactions (especially H_2), they participate in the heating of the diffuse gas through the photo-electric effect and they absorb starlight allowing molecules to survive. With its size distribution spanning the range from big molecules to micron size particles, dust grains can be used as a tracer of the dynamical conditions of the ISM. As it absorbs and gets heated by starlight interstellar dust is a reliable tracer of the star formation activity. Also, being well mixed with the gas, dust emission and extinction is often used to trace the structure of the ISM. Interstellar dust is a complex subject as it involves solid state physics, laboratory experiments, interplanetary samples analysis, numerical simulations (radiative transfer, aggregate growth...), modeling and observations from the ultra-violet to the radio, in emission, extinction and polarization.

Great progress have been made on the subject of interstellar dust since the 1980s, thanks to infrared observations from space with IRAS, COBE, ISO and Spitzer. Moving to the sub-millimeter and millimeter range with Herschel and Planck, we expect to live a similar evolution in our understanding of the interstellar medium in general and of big dust grain in particular. Herschel and Planck will bring key informations on the structure of the ISM, from a few arc-seconds to the whole sky, and from cirrus clouds to dense cores. They will help characterized in detail the evolution of big grains and especially their growth process. Planck will also make a significant contribution as it will make the first all-sky survey of the polarized dust emission, giving access for the first time to the properties of the interstellar magnetic field through all phases of the ISM. Its wavelength range will also allow to describe in more detail the spinning dust emission in the millimeter. In this contribution I present the context in which the interstellar dust community is preparing for Planck and Herschel by giving examples of recent studies and comments on the expected progress.

2 From PAHs to big grains

The emission from interstellar dust is observed from the near-infrared to the radio. It corresponds to the emission from dust grains of size ranging from big molecules to tenths of micron. The size distribution of dust grains is the result of an evolution through a variety of processes tightly related to the dynamics of the ISM. Low energies collisions with the gas leads to accretion of atoms or molecules, and grain-grain collisions produce

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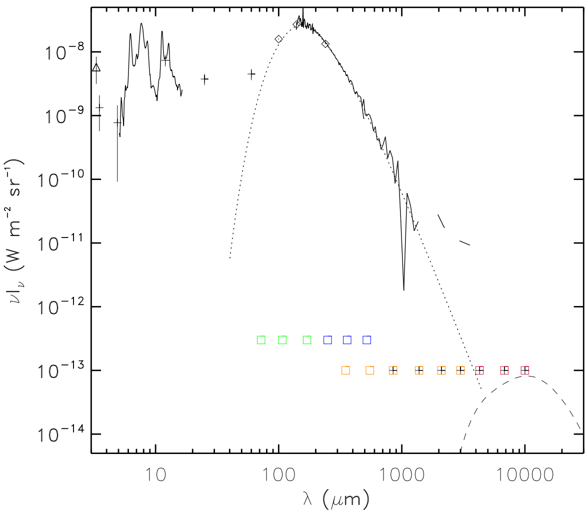

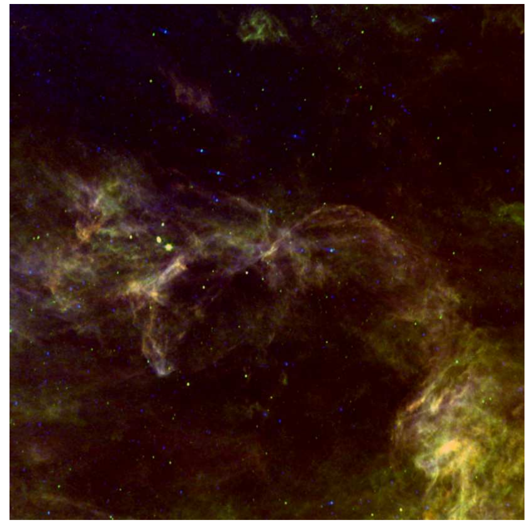

Fig. 1. Left: Emission spectrum from interstellar dust, for a gas column density of $N_H = 10^{20}$ cm^{-2}. Data used in this figure are from ISO, Arome, DIRBE and FIRAS (see Boulanger (1999) for details). The dotted line is a modified black-body spectrum at 17.5 K with $\beta = 2$. The dashed line represents a typical spinning dust emission spectrum, normalized to the 23 GHz map of Miville-Deschênes et al. (2008). The color squares show the central wavelength of the PACS (green), SPIRE (blue), Planck-HFI (orange) and Planck-LFI (red) channels. The Planck polarized channels are indicated with additional crosses. **Right:** $25° \times 25°$ RGB image of the North Celestial Loop as observed by IRAS. Red is 100 μm, green is 60 μm and blue is the average of 12 and 25 μm. Data are from the IRIS dataset (Miville-Deschênes & Lagache 2005). The color variations seen in this image of a diffuse high Galactic latitude cloud, uniformly heated by the interstellar radiation field, reveal variations of the relative abundance of smaller to bigger grains. These variations are seen at all scales in this image which implies that dust grains evolve rather rapidly, even in these diffuse environments.

grain growth (coagulation). At higher energies, typical of interstellar shocks, grains are eroded by the gas or fragmented in grain-grain collisions (Guillet et al. 2007).

Interactions with the radiation field also modify grains. Photons can activate chemical reactions, modify grain structure and even destroy the smaller particles. These smallest dust grains (the PAHs for Polycyclic Aromatic Hydrocarbons) have been the subject of many studies in the past 20 years especially with ISO and Spitzer. Their emission spectrum is now well characterized. The strong emission features of PAHs in the mid-infrared allows to study in details the interstellar physical conditions in photo-dominated regions and the physical properties of these particles, especially their charge state (Flagey et al. 2006). Based on this knowledge, Compiègne et al. (2007) observed the signature of neutral PAHs in a HII region away from the PDR which put constraints on the evolution of these particles in moderate radiation fields. Recently Berné et al. (2007) presented a study based on mid-infrared spectroscopic observations of PDRs obtained with Spitzer. Their detailed analysis of the PAH emission is in favor of a scenario where some PAHs would be the result of fragments detached from bigger grains (the so-called Very Small Grains - VSGs) by photo-evaporation.

PAH emission is now routinely observed in PDRs, at the surface of molecular clouds and in translucent and diffuse clouds. Recently it has also been observed at the surface of disks around Herbig Ae stars at 11.3 μm with VISIR on the VLT (Doucet et al. 2007). These observations offer a new opportunity to study the flaring structure of disks and the evolution of dust grains in the first phases of star and planet formation. Understanding the growth process of interstellar grains is essential in the context of planet formation but it seems that it is an efficient mechanisms even in molecular clouds. There are some observational evidences that grain growth through grain-grain collision can lead to grains with a more open structure, mid-way between compact spheres and fluffy aggregates (Dominik & Tielens 1997). These grains would have a higher surface/mass ratio than compact spheres which modifies their absorption and emission efficiency, leading to a lower equilibrium temperature (Stepnik et al. 2003) and to a modification of their emission spectrum in the far-infrared to millimeter range (Boudet et al. 2005; Meny et al. 2007). Observational evidences of this effect came recently from the detection

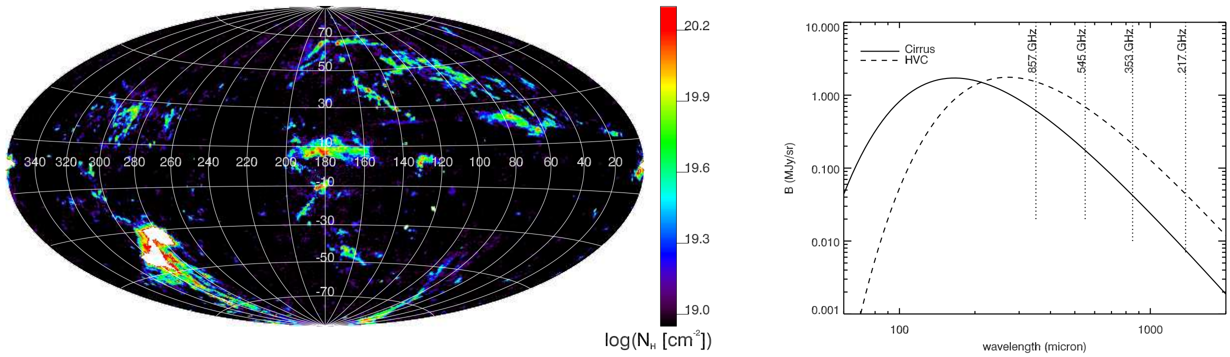

Fig. 2. Left: All-sky map of the High-Velocity Clouds (HVC) at 21 cm as given by the Leiden-Argentine-Bonn survey. The map is centered on the Galactic anti-center region. The bright region at (l∼290, b∼-40) are the Magellanic Clouds. **Right:** Comparison of thermal dust emission for a typical cirrus (T_{dust} = 17.5 K) and a HVC (T_{dust} = 10.7 K). The vertical dotted lines show the expected brightness sensitivity for the four highest frequencies of Planck-HFI after 14 months of observations.

of 304 cold dense cores by the Archeops experiment (Désert et al. 2008).

For now most of the information on the big grain emission in the submm-mm range comes from dedicated observations of selected targets (using SCUBA, PRONAOS, ARCHEOPS for example) or from the all-sky survey of FIRAS on-board COBE. This last experiment provided the only all-sky map of the submm interstellar emission to date but with very limited sensitivity (see the noise level on the spectrum in Fig. 1 - left) and low angular resolution (7°). Planck will improve significantly the situation by providing all-sky maps of the big grain emission at the same resolution than IRAS (5'). In addition, with its better angular resolution (∼ 10" for PACS and ∼ 30" for SPIRE) Herschel will allow to study in greater details the properties of dust emission at small scales in selected regions. This situation is comparable to the leap forward that has been done on the understanding of the PAH emission with the all-sky surveys of IRAS at 12 and 25 μm and the higher resolution observations done with the ISO and Spitzer satellites. With their wavelength range covering the big grain emission (see Fig. 1) and their better angular resolution, Herschel and Planck will certainly modify greatly our understanding of the bigger dust grains and especially of their growth process.

3 Dust, the structure and the mass of the interstellar medium

Being relatively well mixed with the gas, dust grains offer a way to trace the structure of the interstellar medium. This is only true when dust grains are uniformly heated by the radiation field. If not, radiative transfer has to be taken into account to separate contributions from the density and radiation field variations to the emission structure observed (Heitsch et al. 2007). Coupled with the knowledge of how three-dimensional fluctuations are projected on a two-dimensional observed sky, statistical methods can be used to estimate the power spectrum of the density field of interstellar matter in three dimensions in diffuse clouds (see an example of such a diffuse region in Fig. 1 - right). Miville-Deschênes et al. (2007) used this technique to highlight the fact that the density field of interstellar matter follows a power law with a spectral of -3 on average. Furthermore these authors studied the behavior of the non-Gaussianity of the emission fluctuations and could come up with a prescription to simulated realistic non-Gaussian interstellar emission maps. A similar analysis was done by Ingalls et al. (2004) who used 24 μm Spitzer / 25 μm IRAS data of the Gum nebular region to estimate the structure of the medium and the depth of the emitting medium, which corresponds in this case to the depth to which the UV radiation penetrates in the cloud to heat the Very Small Grains.

Observations in the submm-mm range with Herschel and Planck will allow to trace the structure and mass of big grains, including the colder component which is too cold to have a detectable emission in the IRAS bands. Therefore these new experiments will provide a more complete view of interstellar structure, from diffuse to molecular clouds, which is an important aspect of our understanding of the dynamical processes involved in the evolution of matter.

These submm-mm observations will also allow to study the properties of clouds in the Galactic halo and especially High-Velocity Clouds (HVCs - see Fig. 2 - left for an all-sky view of the 21 cm from HVCs). The location and mass of these clouds is still very uncertain but they could well represent the infall of fresh and metal poor gas that is needed to explain the star formation activity of the Galaxy. If, as was shown by Miville-Deschênes et al. (2005), the high-velocity clouds have dust, it has to be cold because of the great distance from radiation source, which would allow Planck to detect them (see Fig. 2 - right). The observation of dust emission from HVCs with Herschel and Planck would provide a new way of estimating the structure, the distance (using the dust temperature) and the mass of these enigmatic clouds.

4 Anomalous microwave emission

One of the greatest challenges of observing the Cosmic Microwave Background (CMB) in the 20-200 GHz range resides in the separation of the CMB and foreground emission. This task is facilitated by the fact that the intensity of the emission from the Galactic interstellar medium reaches a minimum in this range. On the other hand, even if the Galactic emission is weak, it is still stronger than the CMB over a significant fraction of the sky. In addition the identification of the cosmological signal is complicated by the fact that several interstellar emissions are superimposed in this frequency range: free-free, synchrotron, thermal dust and the so-called "anomalous emission" that is either attributed to energetic synchrotron (Bennett et al. 2003) or to small spinning dust grains (Draine & Lazarian 1998). The spectral shape and intensity of the emission is sketched in Fig. 1 (dashed line).

The attribution of the anomalous emission to synchrotron has two important drawback. First the correlation between the anomalous emission and the dust 100 μm emission extends down to low column density cirrus clouds, where there is no star forming activities and no local production of cosmic rays (see Davies et al. (2006)). Second the anomalous emission has been shown to be essentially unpolarized (Battistelli et al. 2006; Miville-Deschênes et al. 2008) which is in favor of the spinning dust hypothesis as it is not expected to be polarized, from theory (Draine & Lazarian 1998) and from extinction measurements of small dust grains (e.g. Martin 2007).

Recently Miville-Deschênes et al. (2008) revisited the analysis of the Galactic emission in the WMAP data. Using a joint analysis of intensity and polarization at 23 GHz they could estimate the anomalous emission over the whole sky (see Fig. 3 - left). This emission is strongly correlated to dust extinction (E(B-V)) which is also in favor of an emission mechanism involving dust grains. Here again, with its better angular resolution and sensitivity, Planck will allow to significantly improve our knowledge of this emission (see Fig. 1).

5 Polarization and magnetic field

Polarization from dust is observed in extinction in the UV to the near-infrared. It is also observed in emission in the far-infrared and submm but observations are still very sparse and mostly confined to bright molecular clouds (Vaillancourt 2007) or to the Galactic plane (Benoit et al. 2004; Ponthieu et al. 2005). Our lack of knowledge of the properties of dust polarized emission, and especially of its power spectrum, is one of the main concern for the analysis of the polarized CMB.

These observations imply that dust grains are aligned on the Galactic magnetic field even if the exact mechanism responsible for this alignment is still a matter of debate. Therefore the Planck/HFI polarization maps of dust thermal emission will provide an unprecedented perspective on the Galactic magnetic field structure in interstellar clouds. For the first time, a detailed study of the structure and intensity of the magnetic fields within nearby interstellar clouds, in relation with their density and velocity structure, will be conducted. Theoretical and numerical simulations studies showed the obvious importance of the magnetic field on the structure and dynamics of the ISM and on the regulation of the star formation efficiency. This is an area of the physics of the interstellar medium where observations has brought very little constraints up to now. In that respect the all-sky maps of dust polarization (and also synchrotron polarization) that Planck will provide will make a significant break-through in our understanding of the ISM.

The analysis of the WMAP 23 GHz polarization data (see Fig. 3) by Miville-Deschênes et al. (2008) gives a first idea on how submm-mm polarization observations can be used to estimate the parameters of the large-scale spiral structure of the magnetic field but also of its turbulent part. With the frequency range sensitive to polarization extending up to 353 GHz, the Planck data will allow to use such method jointly on the dust and synchrotron polarized emissions, and therefore better constrain the properties of the large scale Galactic magnetic field. In addition, the higher sensitivity of the Planck data will allow to perform local statistical

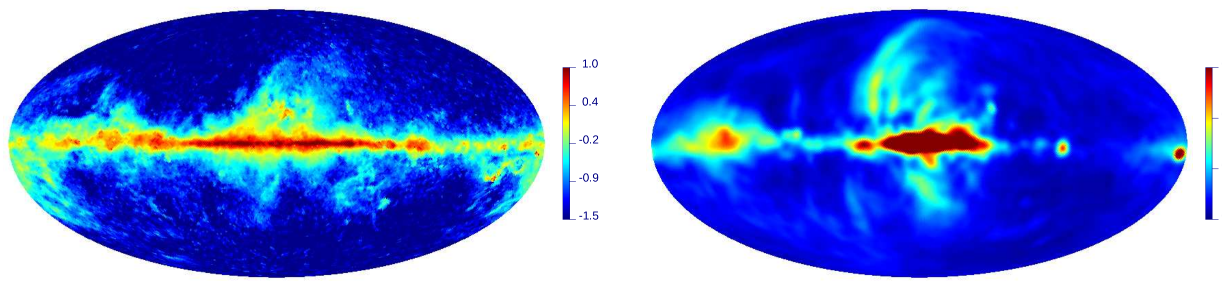

Fig. 3. Left: Anomalous emission at 23 GHz as observed by WMAP (Miville-Deschênes et al. 2008). Units are in $\log_{10}$(mK CMB). **Right:** WMAP polarized intensity at 23 GHz (in mK CMB), smoothed at 5 degrees. At this frequency the interstellar emission is strongly dominated by synchrotron. Planck will provide the first all-sky map of polarized dust emission.

analysis of the polarization angle compared with the amplitude of turbulent motion (the Chandrasekhar-Fermi method) which allow to infer the amplitude of the magnetic field in molecular and cirrus clouds.

Polarization might also help to resolve a long-standing debate about dust emission. The modeling of the dust emission spectrum and of the extinction curve leads to the presence of two populations of big grains, one silicate based and one made of carbonaceous matter. Up to now observations can not indicate whether these grain populations are physically separated or if they compose a mixture. These two dust populations should have different signature in polarization which should help to make progress in this area.

6 Conclusion

Our understanding of interstellar dust has improved spectacularly in the last 25 years, thanks to space observatories like IRAS, COBE, ISO and Spitzer. The combination of all-sky surveys and of higher-resolution observations of specific regions have brought the field of interstellar dust to a high level of complexity. In particular significant progress have ben made in the understanding of the properties and evolution of the smallest dust particles that can be observed in the mid-infrared. The observations of the diffuse PAH emission that were a challenge in the 1980s are now routinely done.

The field of interstellar dust is about to live a similar leap forward with the upcoming Herschel and Planck missions that will provide all-sky surveys and dedicated high-resolution observations of the submm and mm emission from big interstellar grains. In addition Planck will provide detailed mapping of the spinning dust emission, making a direct link with the knowledge obtained recently on interstellar PAHs. Planck will also provide polarization maps in 7 bands, giving access to the structure and intensity of the magnetic field, one of the key information still to be characterized in the ISM. Planck and Herschel will also make important contributions to long-standing questions regarding, for example, the silicate vs carbonaceous grains modeling, the mechanism of grain alignment on the magnetic field, high-velocity clouds, and the grain growth process. It is thus with excitement that we stand on the eve of Herschel and Planck.

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