The Magellanic System: Stars, Gas, and Galaxies
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Dust in the Magellanic Clouds

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Abstract. The Magellanic Clouds are important templates for studying the role interstellar dust plays as actor and tracer of galaxy evolution. Due to their proximity, the Large and Small Magellanic clouds are uniquely suited to put detailed Galactic dust studies in a global context. With a metal abundance lower than that of the Sun, the Magellanic Clouds also permit to characterize interstellar matter composition and structure as a function of metallicity. The presentation of spectacular results from the *AKARI* and *Spitzer* surveys was one of the highlights of this Magellanic Clouds meeting. This paper puts these results in context. I discuss UV extinction and IR emission signatures of carbon and silicate dust. I present diverse evidence of dust processing in the ISM. I illustrate the correlation between the mm emission of dust, and gas column density using Milky Way surveys. I conclude with three main results. Dust in the SMC is not carbon poor. The composition of interstellar dust reflects its processing in interstellar space and thereby depends on local conditions and its past history. In the Magellanic Clouds, far-IR and sub-mm observations are indicating that there may be significantly more cold interstellar matter, cold H I and H_2 gas, than estimated from H I and CO observations.

Keywords. dust, extinction, ISM: evolution, Magellanic Clouds, infrared: galaxies

1. Introduction

Infrared space observatories from *IRAS* to *Spitzer* have laid the groundwork for our current understanding of the properties of interstellar dust. Prior to the opening of infrared space astronomy, dust was mainly known from extinction studies. For most observational astronomers it was considered a mere nuisance in their lives. Today, we realize that dust plays a prominent role as actor and tracer of the structure of matter and of its physical and chemical evolution, as well as of the formation of galaxies, stars and planets.

The Magellanic Clouds are important templates for understanding galaxy evolution. As nicely summarized in SAGE, the *Spitzer* surveys acronym, infrared dust observations bear on three of the key agents of galaxy evolution: interstellar matter, star formation, and the late stages of stellar evolution. Due to their proximity, the Large and Small Magellanic clouds (LMC and SMC) are uniquely suited to put detailed Galactic studies in a global context. For interstellar matter, the *Spitzer* resolution in the near and mid-IR permits to separate individual molecular clouds and star forming regions from the diffuse interstellar medium. Herschel will soon provide comparable sensitivity and resolution in the far-IR. Sub-mm ground observations are also advancing with the LABOCA bolometer array camera on the southern *APEX* sub-mm telescope. With a metal abundance about a factor three (LMC) and eight (SMC) lower than that of the Sun, the Magellanic Clouds permit to characterize interstellar matter composition and structure as a function of metallicity. The small, metal-poor and gas rich SMC is a nearby environment which has some of the characteristics of the early stages of galaxy formation.

The spectacular *Spitzer* color image of the LMC was put forward to announce the meeting. During the conference, several talks and posters detailed the diverse research

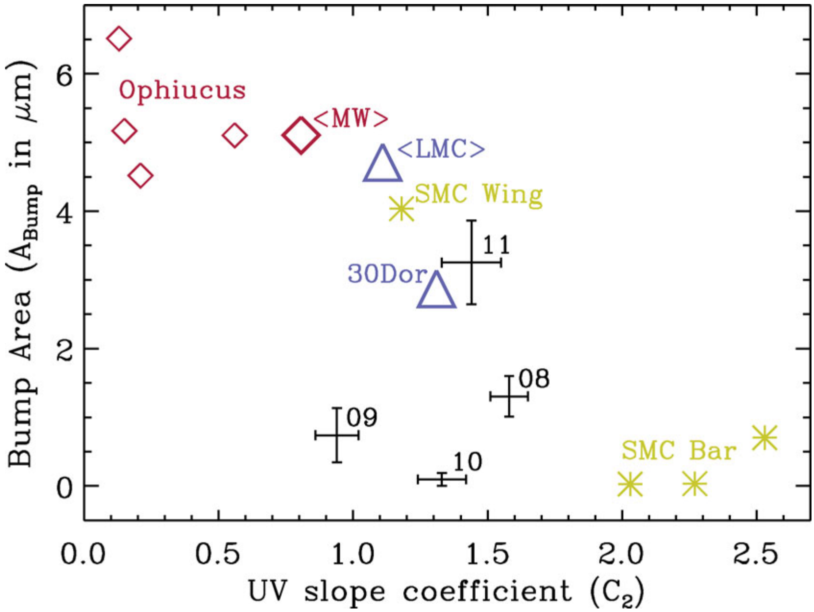

Figure 1. This figure illustrates the difference in the UV extinction curve (UV slope and bump area) between the Milky Way (red diamonds) and the SMC. The mean LMC and 30 Doradus extinction curves from Misselt *et al.* (1999) are plotted with triangles. The stars represent the data gathered by Gordon and Clayton (1998): three bump-free extinction curve towards star forming regions in the SMC Bar and one 30 Doradus-like curve towards the Wing. The numbered points with error bars are results from STIS/*Hubble Space Telescope* observations of a small group of reddened stars located towards the SMC B1 molecular cloud. The four stars are located within a 20$''$ area. The STIS data analysis has been performed by Jesus Appelaniz and will be presented in a forthcoming paper (Boulanger *et al.* in preparation).

which is being carried out with *AKARI* and *Spitzer* observations, in particular the SAGE LMC survey (Meixner *et al.* 2006) and the S^3MC and SAGE SMC surveys (Bolatto *et al.* 2007); Gordon *et al.*, these proceedings). For the first time, I saw dust observations in the fore-front of an extragalactic conference. With this paper, I wish to provide a broader context including Galactic studies, which complements the more specific reports on the Magellanic Clouds data analysis presented in these proceedings.

2. Carbon and silicate dust

The observational constraints on dust, its composition and size distribution, are element abundances and depletions, extinction and scattering properties and the spectral energy distribution (SED) of its emission in the infrared. Most of what we know on interstellar dust comes from Galactic observations.

Interstellar dust comprises several components, including carbonaceous and amorphous silicate grains that are frosted with icy mantles in dense clouds. The amorphous structure of interstellar grains is in contrast with crystalline silicates which have been discovered around some oxygen-rich, evolved stars and comets by the *ISO* satellite.

The smallest grains are aromatic and amorphous hydrocarbon particles containing tens to thousands of carbon atoms per particle. The smallest (sizes less than $\sim$ 1000 atoms) carbon particles are the carriers of the mid-IR bands and are referred to as interstellar Polycyclic Aromatic Hydrocarbons (PAHs). We refer to nanometer size particles as Very Small Grains (VSGs). Both PAHs and VSGs have small heat capacities due to their small

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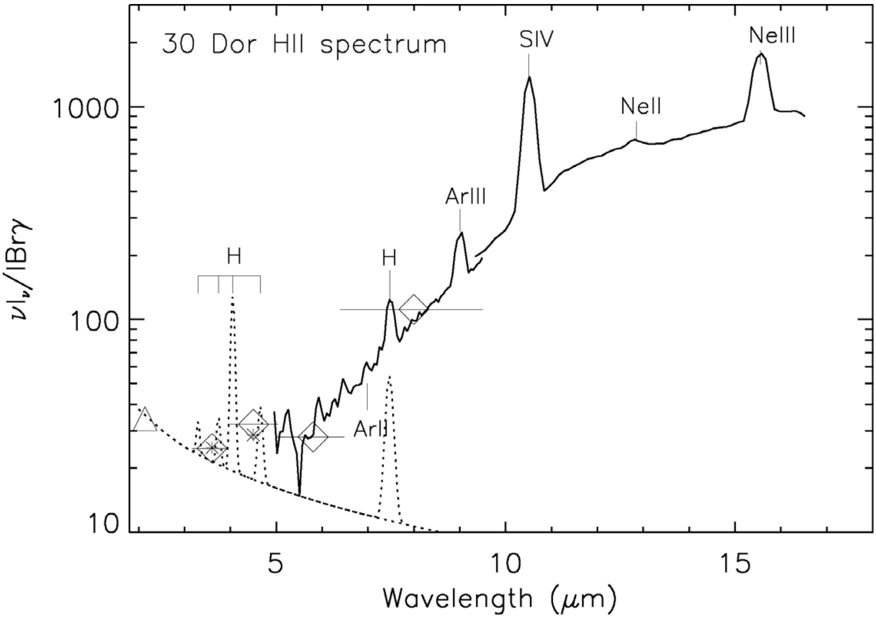

Figure 2. Mid-IR emission spectrum of H II gas near the 30 Doradus super star cluster obtained by correlating IRAC/*Spitzer* (diamonds) and *ISO* spectro-imaging observations with an image in the Brγ hydrogen line. The gas free-free plus the hydrogen lines contribution are shown as a dashed line. This spectrum illustrates PAH destruction in H II gas. The large grains are not hot enough to account for the mid-IR continuum. This continuum must come from VSGs. Note that the continuum is featureless.

dimensions and therefore undergo stochastic heating upon the absorption of photons from the ambient interstellar radiation field (ISRF). They reach peak temperatures from hundreds up to one thousand degrees Kelvin, depending upon their size, and therefore tend to emit most of their thermal energy at wavelengths shortward of 60 μm. In the Solar Neighborhood, stochastically heated grains with sizes smaller than $\sim$1.5 nm account for about 10% of the dust mass and 30% of the power radiated by dust. Since the 9.6 and 18 μm silicate features are not seen in emission — outside high radiation field environments where the equilibrium temperature of dust grains is high enough for them to emit at mid-IR wavelengths — VSGs are thought to be carbon dust.

The larger interstellar particles with dimensions of the order of 100 nm, the "big grains", are in thermal equilibrium with the ISRF. In the Solar Neighborhood, big grains in the diffuse ISM penetrated by UV radiation have temperatures of typically 18 K, and dominate the emission in the far-IR to sub-mm range (the peak of their thermal emission occurs at about 150 μm). The big grains temperature rises with ISRF intensity, $G_{\rm UV}$, as $G_{\rm UV}^{1/\beta}$ wite β in the range 5 to 6.

The Magellanic Clouds are becoming a reference for extragalactic dust. In particular, the 30 Doradus and SMC Bar extinction curves are thought to apply to starburst and low metallicity galaxies in general (Calzetti *et al.* 1994). The Milky Way, LMC and SMC extinction curves have been modeled with a size distribution of carbon and silicate dust (Weingartner and Draine 2001). In these models the 220 nm bump is directly related to the fraction of the dust mass in carbon grains smaller than about 5 nm. Both small silicates and carbon grains in this size range contribute to the UV slope. The differences in the 220 nm bump and the UV slope (Fig. 1) are interpreted as indicating a change in

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the relative fraction of mass in small carbon and silicate dust, with more small silicate dust and less small carbon dust in the SMC bar.

Infrared observations provide complementary evidence for a reduction of the fraction of small carbon dust in low metallicity galaxies like the SMC. Several *ISO* and *Spitzer* spectroscopic and photometric observations show a drop of the PAH emission bands in galaxies of low metallicity (Engelbracht *et al.* 2005). Modeling of the infrared SEDs quantifies this drop in terms of the fraction of the dust mass in PAHs, $q_{\rm PAH}$ (Draine *et al.* 2007). For the SINGS survey galaxies, the median value of $q_{\rm PAH}$ is 3.6% for galaxies with $12 + \log_{10}({\rm O/H})_{\rm gas} > 8.1$ and 1% for lower metallicity galaxies.

The weakness of the PAHs emission bands in the SEDs of low metallicity galaxies has received two interpretations. (1) It traces enhanced destruction of PAHs in regions penetrated by hard ionizing radiation (Madden *et al.* 2006). (2) It reflects a general deficiency of carbon dust due to the delayed injection of carbon dust by AGB winds into the interstellar medium (Galliano *et al.* 2008). The analysis of *Spitzer* observations of evolved stars in the SMC do not support this second interpretation. The first interpretation is supported by the observed destruction of PAHs in H II gas (Contursi *et al.* 2000 and Fig. 2). PAH destruction by ionizing photons may be enhanced in low metallicity galaxies because stars have a stronger ionizing flux but, possibly, mainly because they are small galaxies with a low ISM pressure. The low pressure implies a lower ionized gas density than in large spirals and thereby a larger ionized gas mass for a given ionizing flux.

3. Interstellar dust life cycle

The composition of interstellar dust reflects the action of interstellar processes that contribute to break and re-build grains over timescales much shorter than the renewal timescale by stellar ejecta (Fig. 3). If there is a wide consensus on this conclusion among dust experts, the processes that drive dust evolution in interstellar space are still poorly understood. Understanding interstellar dust evolution is a major challenge underlying many interstellar processes and the interpretation of a wealth of *Spitzer* observations including the Magellanic Clouds survey data.

Dust is subject to processing in the ISM through gas-grain, grain-grain and photon-grain interactions. The degree and nature of the processing depends on the rate and the energy of these interactions both of which are related to the density structure and dynamics of the ISM. High energy gas-grain collisions lead to the erosion of some of the dust mass by sputtering, while low energy collisions lead to the reverse process of gas accretion onto dust. For grain-grain collisions, above some velocity threshold the dust is shattered into smaller fragments, while at lower velocities coagulation occurs. Finally, UV and X-ray photons can alter dust by inducing photon-driven physical and chemical changes including destruction.

High velocity supernova shock waves are thought to be the dominant dust destruction mechanism in the warm ISM. The timescale for dust destruction by sputtering becomes shorter than the gas cooling time for gas temperatures larger than 10^6 K. Gas shock-heated to higher temperatures loses its dust content before it has time to cool (Smith *et al.* 1996). The large variations in the elemental depletions observed in the Galaxy but also in the Magellanic Clouds (Sofia *et al.* 2006) are evidence for the efficiency of dust erosion in the diffuse ISM.

Lower velocity shocks and interstellar turbulence create relative motions between grains that may lead to grain shattering in grain-grain collisions (Falgarone & Puget 1995; Jones *et al.* 1996; Guillet *et al.* 2007). Turbulence might affect the dust evolution more

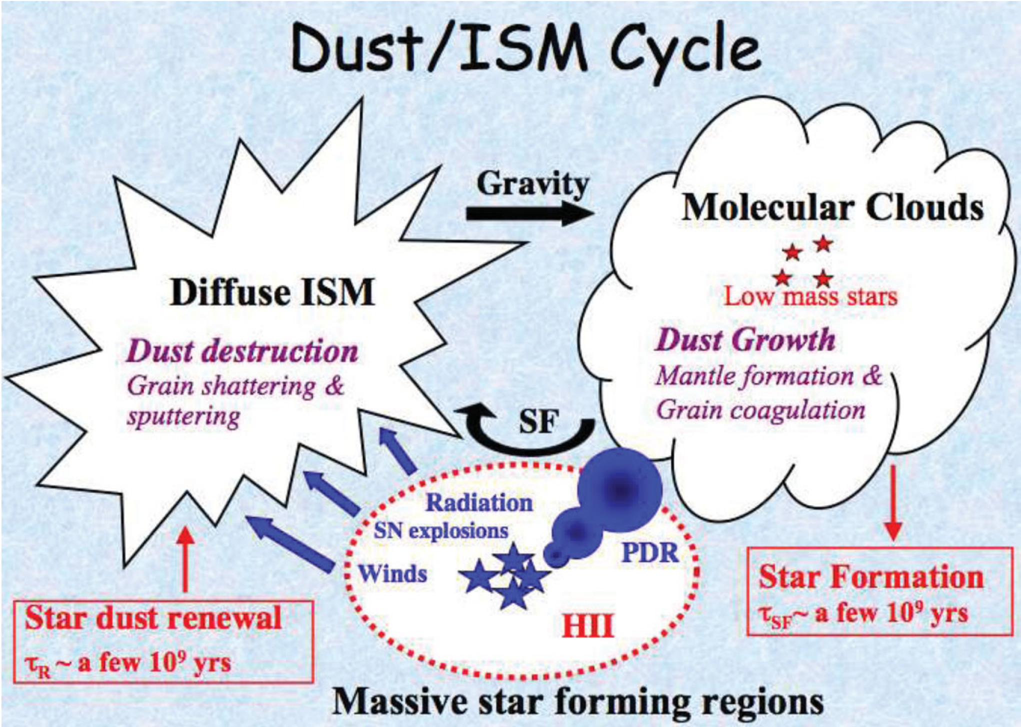

Figure 3. Schematic cartoon of the dust evolution that goes together with the cycling of interstellar matter between diffuse and dense gas phases. The gas cycle and dust evolution is driven by the radiative and mechanical impact of massive star forming regions on their environment. This cycling of matter from the diffuse ISM to molecular clouds occurs on timescales ($<10^7$ yr) commensurate with the lifetime of massive stars. It is happening on timescales three orders of magnitude shorter than the time for dust renewal by stellar ejecta. Observations provide evidence for dust destruction in the diffuse ISM and dust growth in molecular clouds. The composition of interstellar dust reflects its processing in interstellar space and thereby depends on local conditions and its past history.

frequently and thereby more deeply on average than supernovae shock waves. It also continuously cycles dust grains through a variety of physical conditions. Grain shattering impacts the dust size distribution and might be the dominant source of the small interstellar dust particles. Absorption spectroscopy in the mid-IR demonstrates the ubiquitousness of hydrogenated amorphous carbons (a-C:H) in the diffuse interstellar medium of galaxies (Dartois *et al.* 2007). Based on comparison with laboratory samples, Dartois *et al.* (2005) conclude that the interstellar hydrocarbon material consists of aromatic structures bound together with aliphatic carbon chains. Since this material is the main reservoir of interstellar carbon dust, it is considered a likely precursor of VSGs and PAHs. Galactic observations provide spectroscopic evidence for an evolution of small carbon dust, with production of interstellar PAHs out of larger particles, at the surface of molecular clouds (Berné *et al.* 2007).

Evolution processes leave specific signatures on the dust size distribution and thereby on the dust SED which Magellanic Clouds Spitzer surveys are well suited to map. With spectral bands measuring specifically the emission features from PAHs, the mid-IR emission from VSGs and the far-IR emission from big grains, the *Spitzer Space Telescope* imaging instruments IRAC and MIPS are particularly appropriate to map the relative

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abundance of dust in these three size bins. Observations with the IRS spectrometer can provide spectroscopic insight on PAHs and VSGs.

Figs. 1, 2 and 4 illustrate diverse evidence of dust evolution in the Magellanic Clouds. Fig. 1 shows that the UV extinction curve varies from one line of sight to another on small angular scales. Fig. 2 illustrates the destruction of PAHs in H II regions. Fig. 4 illustrates changes in the fraction of the dust mass in PAHs from molecular clouds to the diffuse ISM. Fig. 5 suggests that dust processing can significantly impact the dust-to-gas mass ratio. More evidence was presented in the conference and much of the data analysis remains to be done.

Dust has been introduced in Galactic chemical evolution models (Dwek 1998; Zhukovska *et al.* 2008). These models consider dust mass return from AGB stars, formation of dust in supernovae explosions, dust destruction in the diffuse ISM and dust growth in molecular clouds. Dust processing in the interstellar medium is included with these two processes. The galaxy metallicity affects the evolution of the gas-to-dust mass ratio in two ways. (1) The timescale for dust growth scales as the inverse of the refractory element abundances while the destruction timescale is independent of metallicity. (2) Dust evolution depends on the ratio between the time dust resides in the diffuse ISM versus in molecular clouds, schematically, between interstellar space where dust is destroyed versus where it grows. This ratio depends on the fraction of the gas mass that is in molecular clouds. In large star forming galaxies, most of the gas mass is molecular. In small irregular galaxies like the SMC, possibly because the ISM pressure is lower, most of the gas mass is observed to be in the diffuse ISM. In the bottom plot in Fig. 5, we have used the formula in section 4 of Zhukovska *et al.* (2008) to illustrate the impact these two factors may have on the dust-to-gas mass ratio: its mass weighted value and the difference between the diffuse ISM and molecular clouds. This calculation includes a 10% fraction of the dust mass in dust grains — possibly metallic oxides (Sofia *et al.* 2006) — that resist dust destruction. It is essential to keep nucleation sites to rebuild dust in molecular clouds.

4. Tracing gas with dust emission

Among the various observational means of imaging the structure of interstellar matter, observations of the IR dust emission remain unique for tracing interstellar matter over a wide range of conditions and, in particular, across the key H I to H_2 chemical transition where neither H I nor CO lines are good tracers.

Low metallicity star forming dwarf galaxies are gas rich but have weak CO emission. It is commonly thought that they contain little molecular gas but is this really true? Much of the mass could reside in H_2 gas where CO is photo-dissociated. In low metallicity galaxies, contrary to the Milky Way, CO molecules can only survive in dense clumps of molecular clouds while they are photo-dissociated in the less dense "inter-clump" gas (Lequeux *et al.* 1994). Bot *et al.* (2007) and Leroy *et al.* (2007) address this important question using SMC ground-based sub-mm dust and MIPS 160 μm observations.

Fig. 6 illustrates the correlation between mm dust emission, H I and CO emission in the Solar Neighborhood and in the Galactic plane. The tight correlation between the dust and gas emission supports the use of the long wavelength dust emission as a tracer of gas on large scales in galaxies. Clearly, the mm dust emission is a better tracer than the far-IR emission because it depends linearly on the dust temperature. The accuracy to which the dust optical depth may be determined using far-IR data is limited by differences in dust temperatures among ISM components which are most often ignored. A significant result of the Milky-Way correlation analysis is that the mm dust emissivity per hydrogen atom increases by a factor 2 from the H I gas to molecular clouds. This change can be

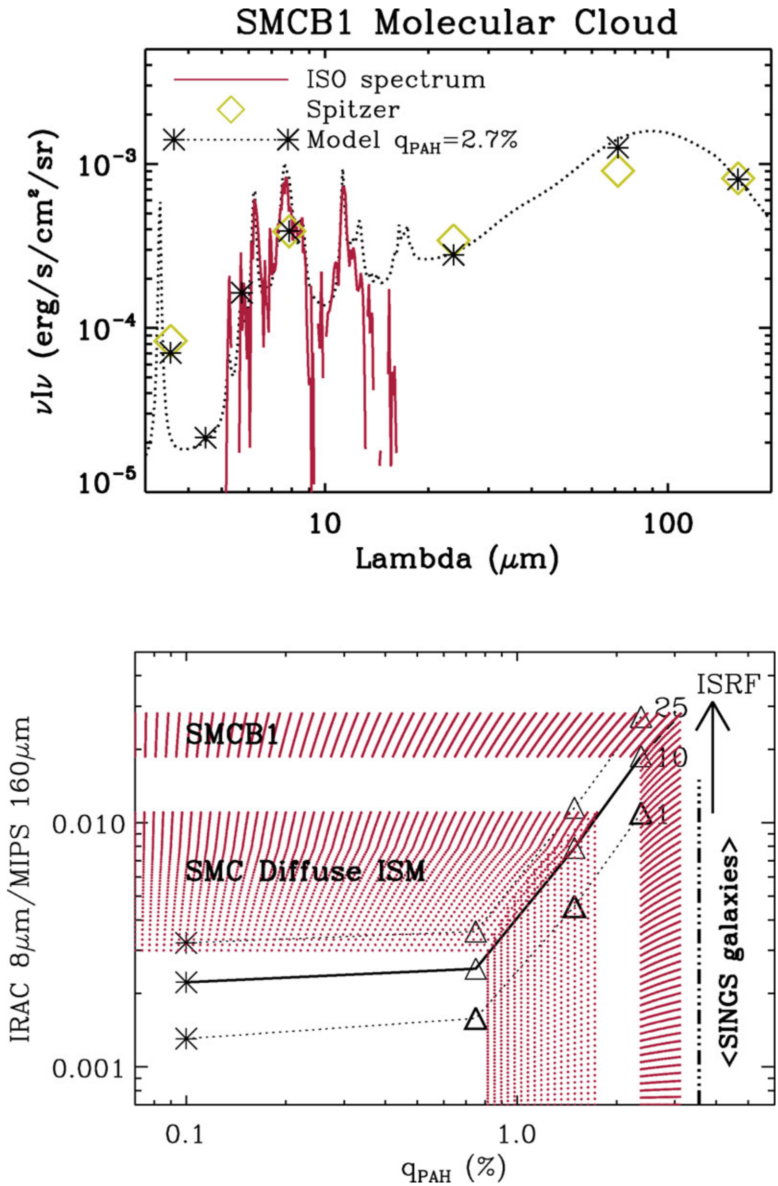

Figure 4. Top: The *ISO* mid-IR spectrum of the SMC molecular cloud SMC B1 (Rubio *et al.* 1996) from Reach *et al.* (2000). The *ISO* spectrum is complemented with IRAC and MIPS photometry obtained with the S^3MC survey (Bollato *et al.* 2007). The dashed line is a Draine & Li (2007) model for a 30 Doradus (LMC2) extinction curve with a fraction of the dust mass in the form of PAHs $q_{\rm PAH} = 2.7\%$, and a radiation field $G_{\rm UV} = 10$ in Solar Neighborhood units. Bottom: The IRAC 8 μm to MIPS 160 μm color ratio is plotted versus $q_{\rm PAH}$ with $G_{\rm UV} = 1$, 10 and 25. The stars are the models of Draine and Li for the linear, 220 nm bump-free SMC UV extinction curve. The triangles are models that fit the 30 Doradus extinction curve. The color ratios measured for the SMC B1 cloud and the diffuse ISM by Bot *et al.* (2004) are marked with their error bar by the horizontal hatched area. The models are used to convert these colors in estimates of $q_{\rm PAH}$. The median value found in Solar metallicity SINGs galaxies (Draine *et al.* 2007) is marked with a dot dashed line.

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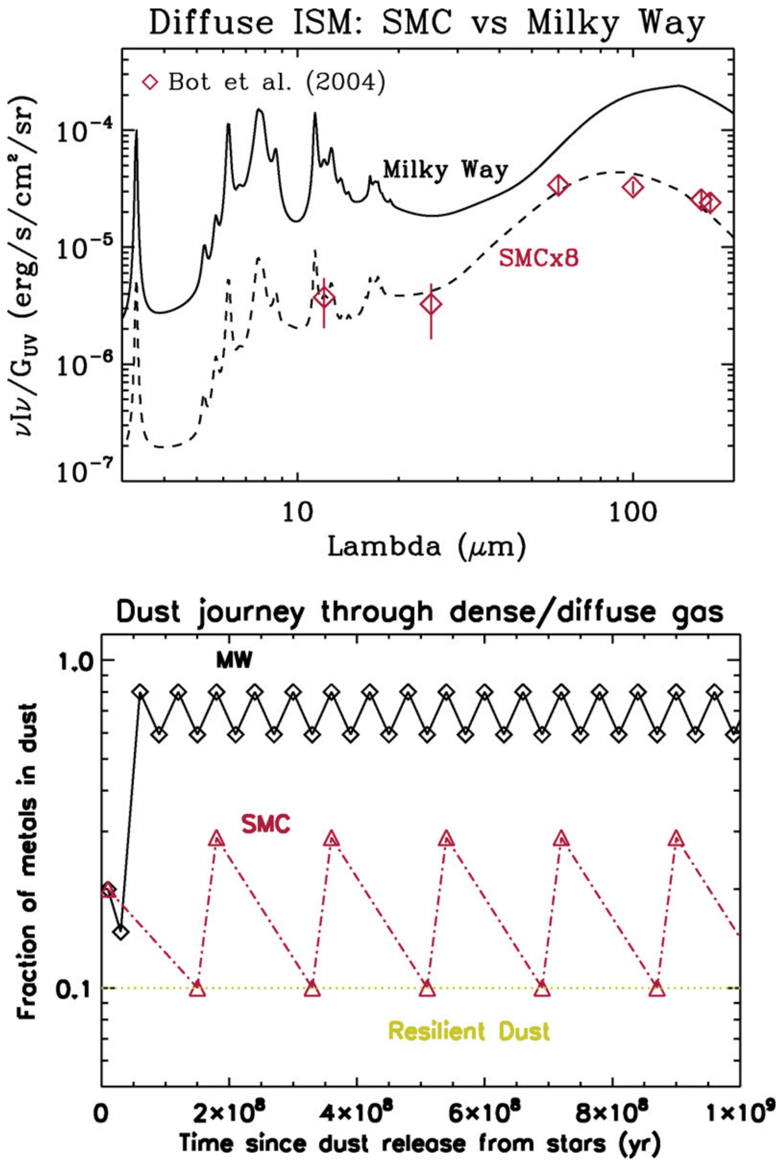

Figure 5. Top: The diffuse ISM SMC SED from Bot *et al.* (2004) is compared to that of the Solar Neighborhood represented here by the Draine and Li (2007) model fit. The model is plotted for a gas column density of 10^{21} H cm^{-2}. The dashed line is a Draine and Li model — for the 30 Doradus extinction curve and $q_{\rm PAH} = 1.5\%$ and a radiation field $G_{\rm UV} = 10$ in Solar Neighborhood units — which fits the mid-IR and far-IR SMC data. The SMC data points and model have been scaled down by this $G_{\rm UV}$ factor and multiplied by 8 to account for the difference in radiation field intensity and metallicity, respectively. The systematic shift between the two SEDs has been interpreted as indicating a drop in dust-to-gas mass ratio from the Milky Way to the SMC larger than the metallicity difference (Bot *et al.* 2004).
Bottom: Schematic model to illustrate the impact of the metallicity on the evolution of the dust-to-gas mass ratio between the diffuse ISM, where dust destruction occurs, and molecular clouds, where refractory gas atoms accrete on dust. This calculation is based on the Zhukovska *et al.* (2008) dust evolution model. Note the difference in the mean fraction of metals in dust and the range of variations introduced by ISM processing. The initial fraction is assumed to be 20%. The large number of cycles illustrates the fact that the cycling time is much smaller than the dust renewal time by stellar ejecta.

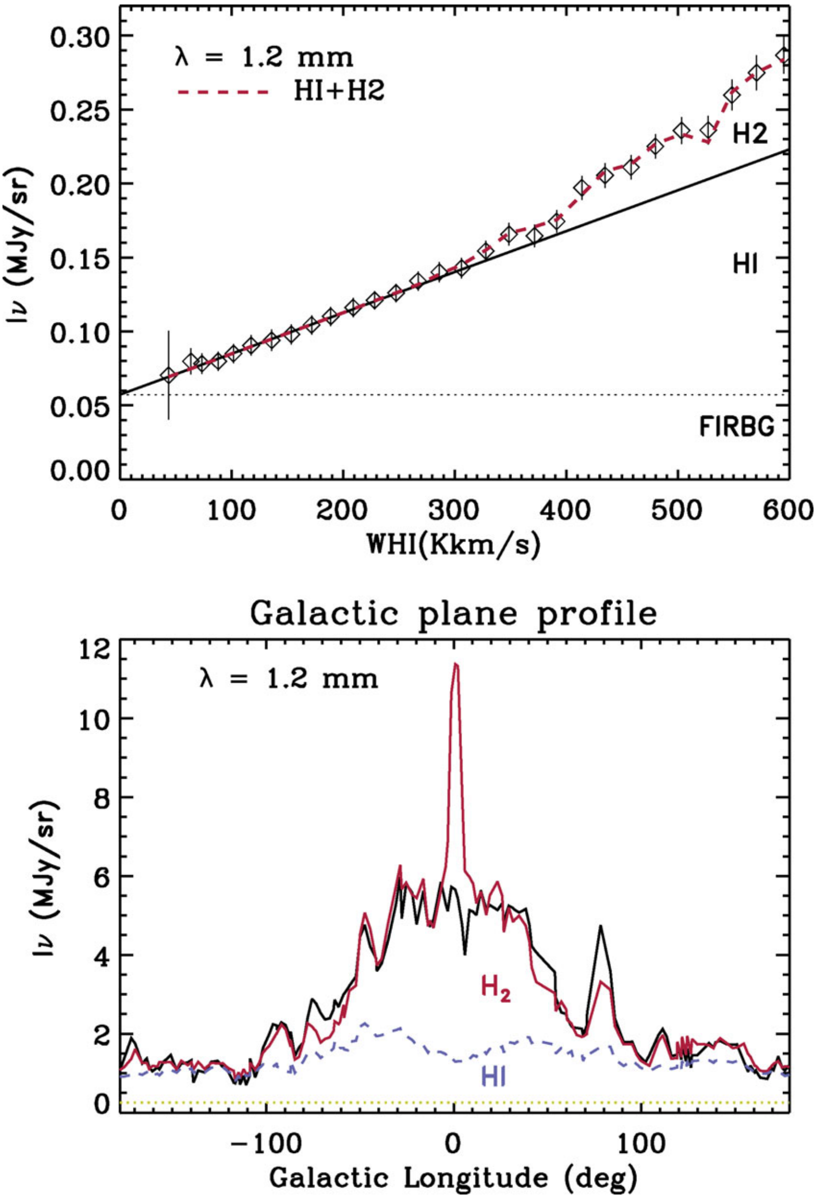

Figure 6. Correlation between 1.2 mm dust (*FIRAS/COBE* data) and gas emission (H I Leiden Dwingeloo survey and CO from Dame *et al.* 2001) in the Milky Way at high Galactic latitude ($|b| > 10°$) and along the Galactic plane. The red lines (dashed in the top figure and solid in the bottom one) is a data fit where the dust emission is expressed as a linear combination of the H I and CO emission. In the top figure the H I emission is the integrated line emission in $\mathrm{K\,km\,s^{-1}}$. The offset is the far-IR extragalactic background (FIRBG). Note the absence of a dust counterpart to the CO intensity peak in the Galactic center. This is also seen when comparing CO and γ rays emission (Blitz *et al.* 1985). It reflects a much larger CO luminosity to H_2 mass ratio in the Galactic center than in the Molecular Ring.

partially accounted by an increase in the dust-to-gas mass ratio associated with grain growth in dense gas. It is likely that it also reflects a change in emission properties.

In their analysis of the diffuse emission in the SAGE LMC data, Bernard *et al.* (2008) report a similar study but a different result. A linear correlation between the far-IR

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optical depth and the gas column density is observed only in the external regions of the LMC. Within the LMC, excess far-IR is observed with respect to that correlation. This far-IR excess emission may indicate an additional gas component unaccounted for by H I and CO emission. Assuming a constant dust abundance and emissivity in the atomic and molecular gas phases, this additional gas component would have twice the known H I mass. It is plausible that the far-IR excess is due to cold atomic gas optically thick in the 21 cm line. H_2 gas with no CO emission is also a possible explanation.The SMC studies of Bot *et al.* (2007) and Leroy *et al.* (2007) reach a similar conclusion. Dust observations are indicating that there may be significantly more cold interstellar matter, cold H I and H_2 gas, than estimated from H I and CO observations.

5. Summary

The presentation of spectacular results from *AKARI* and *Spitzer* was one of the highlights of this Magellanic Clouds meeting. This paper puts them in context. I list a few conclusions I am confident with.

• Dust in low metallicity galaxies is not carbon poor. After the first *ISO* detections, there are now multiple spectroscopic evidence for the presence of small carbon dust in the SMC. The weakness of the PAH emission bands in the SEDs of low metallicity galaxies results from destruction of PAHs in star forming regions and in the diffuse ISM.

• There is diverse evidence for evolution of interstellar dust within the Magellanic Clouds. The UV extinction curve, gas depletions and infrared SEDs are observed to change. These changes stress the importance of characterizing dust processing in interstellar space. The data interpretation needs to be supported by models of dust evolution taking into account the metallicity.

• Dust long wavelength emission is a promising complement to CO to trace cold interstellar matter in galaxies. Galactic observations show a linear correlation between mm dust emission, H I and CO emission in the Solar Neighborhood and in the Galactic plane. In the Magellanic Clouds, far-IR and sub-mm observations are indicating that there may be significantly more cold interstellar matter, cold H I and H_2 gas, than estimated from H I and CO observations.

• The progress in the *Spitzer* data analysis promises new results in the near future. *Herschel* and *ALMA* will soon open complementary perspectives.

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