# XIII

# RELATIONSHIPS TO INTERSTELLAR DUST

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# Properties of Interstellar Dust

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**Abstract.** In this review, the picture of the interstellar dust is outlined from the viewpoint of its role in galactic evolution. The modern concept of distinct dust populations is presented. The properties of the dust grains in the diffuse interstellar medium and in the molecular clouds are described. Some unsolved problems and future perspectives of interstellar dust research are pointed out.

## 1. Introduction

Impressive progress has been achieved during the last two decades in the research field of the interstellar dust. Important steps on this way were the following:

- The identification of chemical bonds in dust solids by IR spectroscopy in collaboration with laboratory studies of cosmic dust analogues
- The detection of stellar sources of permanent galactic dust input and the evaluation of interstellar dust destruction
- The definition of distinct dust populations and the new understanding of the role of dust within galactic evolution
- The study of presolar components of solar system solids

## 2. The multi-population dust

Dust in the Galaxy consists of several distiguishable multi-component particulates typical of the environment in which the grains are formed or are strongly modified. There are at least four of such dust populations: stardust, dust in the clouds of the diffuse interstellar medium (ISM), dust in molecular clouds (MCs), and circumstellar (CS) dust in young stellar objects (YSOs) and in planetary systems (Dorschner & Henning 1995).

Fig. 1 illustrates the relationships between the different dust populations. In the stellar winds of evolved stars, new dust is formed and is injected into interstellar space (see Sedlmayr 1994 and literature therein). Here, the young stardust is mixed with old, heavily processed diffuse ISM dust, and is subjected to manifold environmental factors, e.g. UV radiation and supernova shocks (Draine 1990, Tielens et al. 1994).

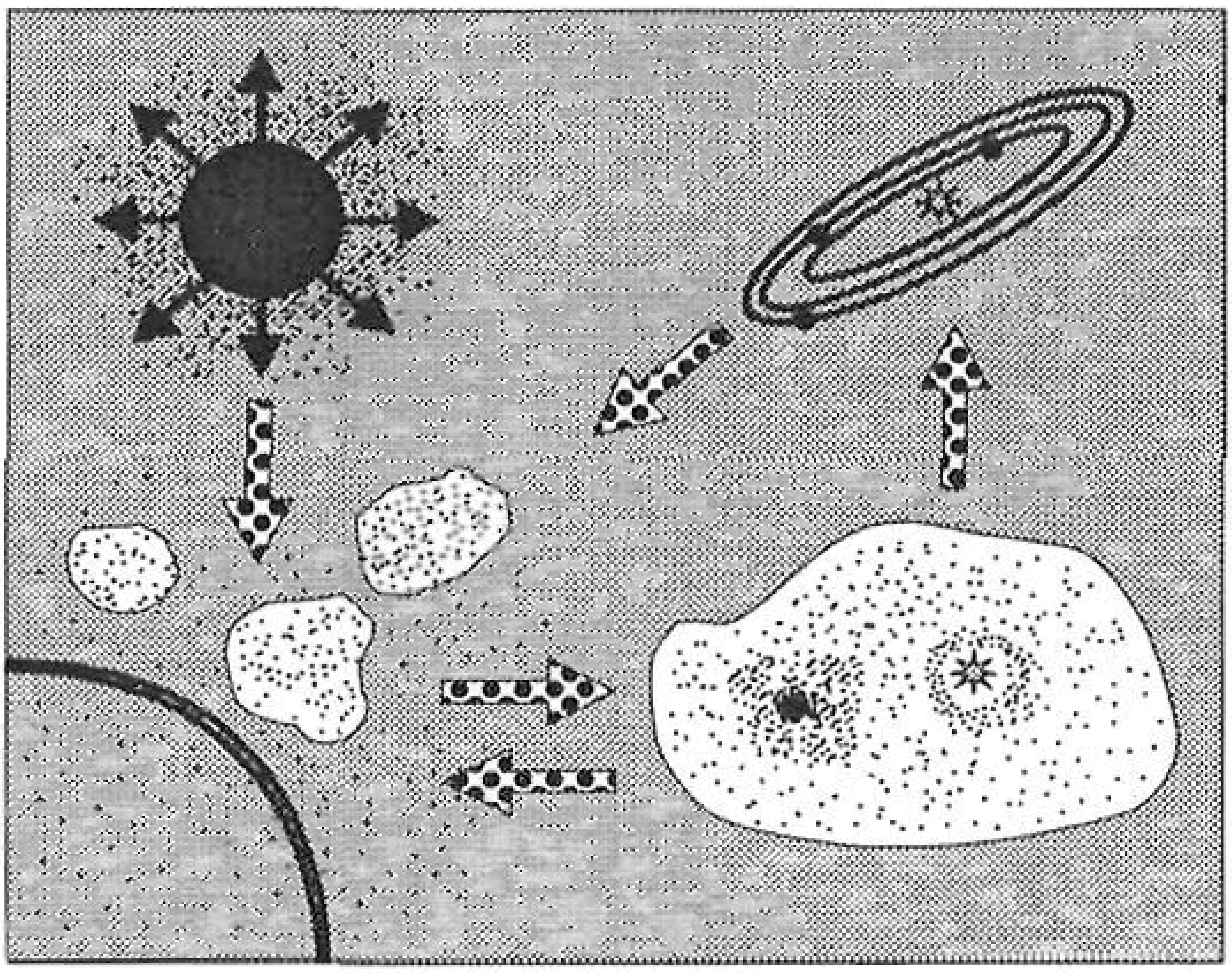

Figure 1. Dust populations and galactic evolution: stardust (top l.); diffuse ISM dust (bottom l.) with passing supernova shocks; dust in MCs and star-forming regions (bottom r.); CS dust in YSOs and planetary systems (top r.). The arrows point to dust transfer. The scheme is based on an idea by Tielens & Allamandola (1987).

In the cool MCs, the grains are coated by ice mantles, and star birth has dramatic consequences. The volatile grain mantles evaporate, and a small part of the ices is transformed to organic refractories by photolysis (Greenberg 1984, Sandford et al. 1991). Further, the environment of protostars is a breeding ground for solids on all size scales, from dust grains to planets (Hanner 1995). Thus, star formation is a sink of old as well as a source of new dust.

Main sequence stars with circumstellar (planetary) systems and, to a much larger extent, giant stars are long-time dust sources. The time-scale of this stellar dust production is as the order of $10^9$ years whereas the time-scale of dust destruction in diffuse clouds and the lifetime of MCs are as the order of $10^8$ and $10^7$ years, respectively (Jones & Tielens 1994). Thus, CS dust formation alone is not sufficient to account for the observed ISM dust density. The elemental depletion in the interstellar gas underlines that dust also must be formed in the ISM itself (Draine 1994).

## 3. Properties of the diffuse ISM dust

Current models of the diffuse ISM dust are based on direct observational evidence, including the average interstellar extinction curve, the diagnostic IR absorption bands, and data of thermal dust emission. For the sake of brevity, this discussion must be confined to these key observations, and other interstellar dust phenomena, such as polarization and light scattering, must be omitted.

### 3.1. Dust extinction

The interstellar extinction curve is a normalized plot of measured colour excesses of stars reddened by interstellar extinction vs. wavenumber. It can be separated into individual components, each of which carries information about different grain size modes (Greenberg 1973, Mathis 1993, Cardelli 1994).

The NIR part of the extinction curve is remarkably uniform in the Galaxy. The visual part forms the well-known $1/\lambda$-law with the characteristic slope parameter $R = A_V/E(B-V)$ ($A_V$ visual extinction, $E(B-V)$ visual colour excess). The value $R$=3.1 typical of the diffuse ISM dust points to grain sizes around 0.1 $\mu$m. They are called "big" grains because they are much larger than those responsible for the UV extinction. Superimposed on the continuous shape of the extinction curve is a strong absorption band (the "bump"). Its wavelength position is fixed at 217.5 nm, but the band width shows considerable scatter from star to star. The band is thought to be due to surface plasmons in nm-sized particles of graphitic carbon. The non-linear extinction rise in the FUV beyond the bump may also be due to nm-sized grains.

### 3.2. Size distribution function

It is not possible to derive the size distribution function $n(a)$, $a$ being the particle radius, from the extinction curve in a mathematically unique way. However, Mathis et al. (1977, MRN) showed that silicate and graphite grains following the size distribution function $n(a) \propto a^{-3.5}$ within $250 \geq a \geq 5$ nm can satisfactorily reproduce the extinction curve. Power laws of this type suggest that fragmentation significantly affects the grain size spectrum.

A classical approach to the determination of the grain size distribution was proposed as early as the 1940s by Oort & van de Hulst (1946) who assumed a steady state between collisional grain destruction and continuous grain growth by condensation of gas. Based on the same assumption, Hong & Greenberg (1978) obtained the exponential size distribution function $n(a) \propto \exp(-Ca^3)$.

### 3.3. IR dust emission

The existence of nm-sized grains received strong support by the spectacular IRAS discovery of the cirrus-like distributed galactic dust emission (Low et al. 1984, see Cutri & Latter 1994). The cirrus intensity in the IRAS passbands at 100 and 60 $\mu$m can be explained as being due to the emission of dust grains in thermal equilibrium with the interstellar radiation field. The blackbody character of the FIR emission has been confirmed by the COBE FIRAS measurements suggesting a typical dust temperature $T$=18$\pm$2 K (Draine 1994). In contrast to the FIR, the intensities in the 25 and 12 $\mu$m passbands have been measured far in excess of the equilibrium emission (Boulanger et al. 1985). This excess is attributed to very small grains stochastically heated to some hundred K by the absorption of single UV photons. This non-equilibrium dust emission mechanism was originally proposed by Sellgren (1984).

### 3.4. Diagnostic IR bands

Astronomical IR spectroscopy has detected absorption bands of the diffuse ISM dust in the spectra of background sources, e.g. GC IRS7 (Aitken et al. 1989).

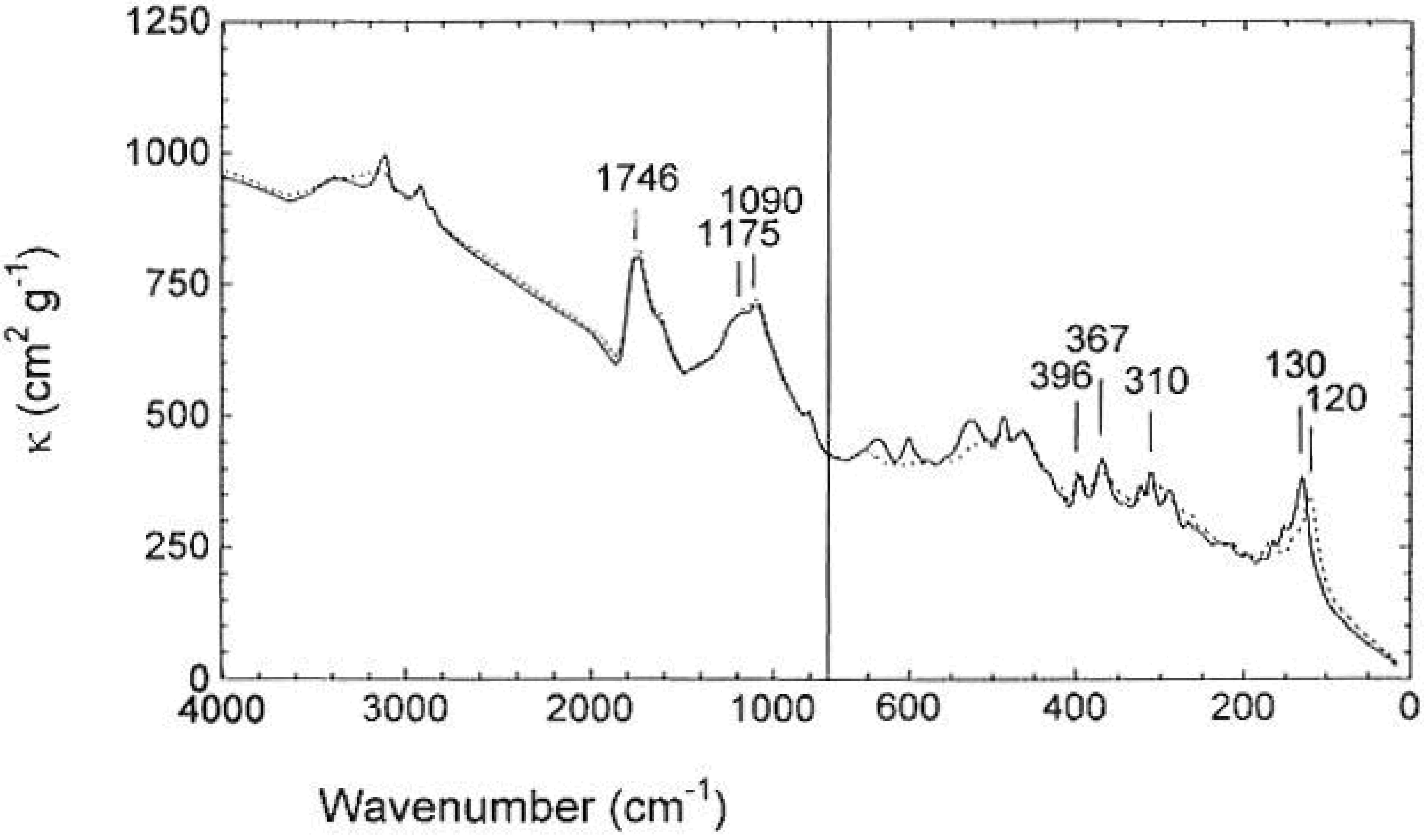


Figure 2. Mass absorption coefficient of Murchison diamonds measured at $T$=10K (solid line) and $T$=300K (dotted line). The absorption bands are due to active groups chemisorbed at the diamond surface. The strong FIR band at 120/130 nm could make available future observations of interstellar diamond dust (Mutschke et al. 1995).

Strong features at 9.7 and 18.7 $\mu$m could be identified with vibrational bands of silicates. Silicate bands have also been found in the spectra of oxygen-rich AGB stars. Laboratory work has shown that the interstellar and circumstellar silicate dust consists of amorphous Mg-Fe-silicates (for the early work see the review by Krätschmer 1988; Jäger at al. 1994, Dorschner et al. 1995).

A blended interstellar band detected in the range 3.4-3.5 $\mu$m could be attributed to C-H stretching vibrations of aliphatic hydrocarbons in carbonaceo dust with tetrahedrally (sp$^3$) bonded carbon atoms (Pendleton et al. 199 correlation found between the strengths of the Si-O and the C-H vibra bands (Sandford et al. 1995) indicates a close connection of both compo The interstellar hydrocarbon profile shows a striking similarity to that o carbonaceous material of the Murchison meteorite (Pendleton 1994) and is v similar to that of organic residues obtained by UV photolysis of ice-mixture simulating volatile molecular cloud dust (Sandford et al. 1991, 1995). The latter finding is a strong argument in favour of photolytic processing during cyclic passages of dust in and out of molecular clouds (Greenberg 1984).

This carbonaceous dust must, however, be quite different from the 217.5-nm-band carrier, which is assumed to be caused by sp$^2$ (trigonally) bonded carbon. Up to now, only evidence of sp$^3$ (tetrahedrally) bonded carbon has been detected. Laboratory studies suggest that the carbon grains condensing in C star winds should contain tetrahedrally bonded carbon rather than graphitic carbon. The dilemma has been augmented by the discovery of the presolar diamonds in meteorites which are supposedly of interstellar origin (Ott 1993).

These diamonds are 400 times (by mass) as abundant as presolar graphite grains in the same meteorites. Fig. 2 shows the spectra of Murchison diamonds in the range 2.5-500 $\mu m$ studied in Jena (Mutschke et al. 1995).

In the context of carbon dust, the group of unidentified IR bands (UIBs) must be mentioned. These strong emission bands mainly occur in carbon-rich objects with enhanced UV or optical radiation fields, e.g., planetary nebulae, reflection nebulae, Wolf-Rayet stars, but they have also been observed as large-scale galactic emission (Sellgren 1994). Laboratory analogue experiments suggest a connection to carbon, but, in the strict sense, the origin of these features is not yet understood.

Table 1. Current grain models for the diffuse ISM.
Grain composition: AC amorphous carbon, GRA graphite, HAC hydrogenated amorphous carbon, I iron, PAH polycyclic aromatic hydrocarbons, RO refractory organics, SIL silicates.
Size distribution: d discrete size or narrow size intervall, exp exponential law, g giant grains in the order of magnitude 10 $\mu m$, p power law (MRN), vs very small grains

| Authors (year) | Grain type Composition | Size distr. function | 217.5 nm carrier |
|---|---|---|---|
| Draine & Lee (1984) | bare grains SIL, GRA | p | GRA |
| Chlewicki & Laureijs (1988) | core-mantle + bare grains core: SIL, mantle: RO, bare: GRA, I, PAH | exp, d | GRA |
| Greenberg (1989) | core-mantle + bare grains core: SIL, mantle: RO, bare: GRA | exp, d | GRA |
| Williams (1989) | core-mantle + bare grains, core,bare: SIL, mantle: HAC | p, vs | SIL |
| Mathis & Whiffen (1989) | coagulated + bare grains coagulated: SIL, GRA, HAC, bare: GRA | p | GRA |
| Désert et al. (1990) | core-mantle + bare grains, core: SIL, mantle: RO, bare: AC, PAH | p, vs | vs |
| Sorrell (1990) | bare grains SIL, AC, GRA | d | GRA |
| Rowan-Robinson (1992) | bare grains SIL, AC, GRA | d, g | GRA |
| Siebenmorgen & Krügel (1992) | bare grains SIL, AC, GRA, PAH | p | GRA |

### 3.5. Current dust models

The present state of understanding interstellar dust is reflected by the current dust models listed in Table 1. The following conclusions on the diffuse ISM dust can be drawn:

- Mg-Fe silicates are considered to be the most reliably identified dust component.
- Almost all models include a graphitic-carbon dust component which is responsible for the extinction bump at 217.5 nm. However, the carbon $sp^2/sp^3$ dilemma shows that there are some problems with this assumption
- There is no consent among the model designers about additional (mainly carbonaceous) components like AC, HAC, RO, PAH. The addition of further components cannot be ruled out.

Much experimental work has been focussed on PAH molecules as an ISM ingredient (Allamandola et al. 1989). As a matter of fact, PAH bands are positioned near the UIBs, but a convincing break-through of the identification problem has not been reached yet. Since PAHs are an important link in the chain from carbon molecules to carbon/carbonaceous solids, the investigation of these compounds is important for the study of the formation of carbon grains (Tielens 1990, Sedlmayr 1994).

## 4. Properties of the molecular cloud dust

### 4.1. Interstellar ices

Small nearby molecular clouds have been known for a long time as "dark clouds . Since they produce apparent holes in the stellar distribution of the Milky Way, Barnard called them even "black holes". The nature of these clouds became clearer only after large MCs had been discovered by observations of their CO molecules. MCs turned out to be a special ISM phase characterized by the occurrence of molecules, high gas densities, large dust extinction, and low temperatures. Molecules freezing out of the gas and precipitating onto the dust grains or being formed by chemical reactions at the grain surfaces produce ice mantles. In contrast to the diffuse ISM, in the MC environment which is shielded against stellar radiation by the dust extinction, ices are stable and represent the most important dust component. IR spectroscopy has detected many vibrational bands of molecular cloud ices (Table 2, Whittet 1993) in addition to features of refractory components, e.g., silicates.

### 4.2. Extinction in molecular clouds and star-forming regions

The extinction curves in MCs are flatter than in the diffuse ISM clouds, and their slope parameters have, therefore, larger values in the range $R$=4-6. This indicates a shift of the size distribution towards larger grains. Calculations show that grain growth by accretion of molecules alone is too slow to produce such big grains in the short lifetime of a molecular cloud. A process that apparently can guarantee a fast growth of the grains to the necessary size is the coagulation of grains as a consequence of sticking after soft collisions have occurred.

Table 2. Ice species detected in molecular clouds. From the minor ingredients, the identification of which is not so reliable than that of the main species, only two examples are listed. They are to demonstrate that apart from H, C, and O also the elements N and S could play an important role in volatile MC dust components.

| **Species** | **Wavelength** ($\mu$m) | **Vibrational mode** | **Abundance** ($H_2O$=1) |
|---|---|---|---|
| *Main species:* | | | |
| $H_2O$ | 3.08 | OH streching | 1 |
| | 6.0 | HOH bending | |
| | 13.3 | libration | |
| | 45 | transversal optical | |
| CO | 4.67 | CO streching | 0...0.5 |
| $CO_2$ | 4.27 | CO streching | |
| | 15.2 | OCO bending | 0...0.2 |
| $CH_3OH$ | 3.53 | CH stretching | 0.05...0.10 |
| | 6.85 | $CH_3$ deformation? | |
| | 8.86 | $CH_3$ rocking | |
| | 9.75 | CO stretching | |
| *Minor ingredients:* | | | |
| XCN | 4.63 | CN stretching? | |
| Unknown (S-bearing?) | 4.9 | CO stretching in OCS?? | |

## 5. Some unsolved problems and future perspectives.

There are many open questions on interstellar dust which are a great challenge especially to the laboratory astrophysics:

- **Unidentified interstellar bands.** In addition to the UIBs mentioned above, about 200 diffuse interstellar bands in the visual and NIR range (Jenniskens & Désert 1993, Herbig 1995), presenting the biggest puzzle of the astronomical spectroscopy, are waiting for their identification. Are they due to molecules or solids? Could they be unknown fingerprints of carbon dust?

- **The well-known carbon dilemma.** Graphitic carbon seems to be the best candidate of the 217.5 nm band carrier, but clear evidence only exists for $sp^3$-bonded carbon. Could effective interstellar graphitization be the solution? (Ogmen & Duley 1988, Sorrell 1990, Mennella et al. 1995)

- **Additional interstellar dust components.** There is some evidence that the lists of interstellar dust components in Tables 1 and 2 are not complete. Could oxides solve some interstellar depletion problems (Sofia et al. 1994)? Do the FeS inclusions in the GEMS (Bradley 1995) confirm the existence of interstellar sulfide grains proposed by Begemann et al. (1994)? How large are the abundances of $NH_3$ and $CH_4$ in the molecular cloud ices really, which are predicted by the theory, but for which only tentative evidence exists (Whittet 1993)?

- **The silicon carbide problem.** The 11.3 $\mu$m emission band of carbon stars is attributed to silicon carbide. Up to now, neither circumstellar nor interstellar SiC absorption has been observed. However, primitive meteorites contain big presolar SiC grains. Where did all the small SiC stardust grains responsible for the 11.3 $\mu$m emission band go (Kozasa et al. 1995)?

The 1990s have been heralded by the National Research Council (1991) as the "decade of the IR". Progress of relevance to dust research can be expected from ground-based and air-borne (SOFIA) as well as from satellite IR spectroscopy (ISO, FIRST, SIRTF) in close collaboration with experimental work in laboratory astrophysics facilities. The laboratory measurements will not only aim at the determination of optical constants of bulk material, but also at the study of the properties of isolated dust grains of complicated shape and composition. The study of chemical surface reactions and grain growth by accretion and coagulation, as well as the investigation of clusters in the transition region molecule/solid will be of special importance.

Future studies of presolar components of IDPs and unmetamorphosed meteorites are expected to bring to light additional interstellar traces. Important new insights into the properties of the diffuse ISM dust will be gained by interplanetary probes studying in greater detail the grains penetrating the solar system. Determinations of the chemical composition by impact mass spectrometry (beginning with the Cassini mission), direct measurements of grain sizes by a new generation of dust detectors that can simultaneously determine grain masses and sizes, and, finally, dust collection and recovery would form a new empirical base for drawing a more realistic picture of the local interstellar dust.

A further highly significant step will be the in-situ investigation of cometary ices and dust crusts (beginning with the Rosetta mission). If cometary nuclei do contain unchanged molecular cloud dust ices, then such missions could also make available the volatile components of the interstellar dust to laboratory studies. The greatest information gain, however, would be achieved by recovering cometary nucleus material.

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