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Dust metamorphosis in the galaxy

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Summary. Cosmic dust grains play an important role for the thermal, dynamical, and chemical structure of the interstellar medium. This is especially true for the star formation process and the late stages of stellar evolution. Dust grains determine the spectral appearance of protostars, very young stellar objects with disk-like structures as well as of evolved stars with circumstellar envelopes.

In this review, we will demonstrate that solid particles in interstellar space are both agent and subject of galactic evolution. We will especially discuss the different dust populations in circumstellar envelopes, the diffuse interstellar medium, and the molecular clouds with strong emphasis on the evolutionary aspects and the metamorphosis of these populations.

1 Introduction

In the last decade, the field of cosmic dust research has undergone a dramatic development made possible by the rapid progress of ground-based and extraterrestrial IR observations and by establishing laboratory groups accumulating material data of cosmic dust analogues. The combination of both has resulted in the certain identification and the quantitative analysis of solid-state bands due to chemical groups occurring in interstellar and circumstellar solids. Apart from the considerable progress in understanding the chemical nature of the grains, IR observations yielded strong evidence for the occurrence of very small dust grains closing the size gap between molecules and solids. The identification of different chemical components and the new picture of very different grain size modes formed the base for the definition of dust populations and the search for their origin.

At the same period, the discovery of presolar grains preserved in primitive solar system solids paved the way for a new empirical base of dust research. For the first time, material data of intrinsically extrasolar solids derived by chemical and mineralogical techniques opened completely new insights into the nature of dust grain material.

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Table 1. Important conference proceedings and monographs on cosmic dust published after 1989

Editor(s), author(s) (year) Meeting / review	Title	Short characterization
Allamandola and Tielens (1989) IAU Symp. 135, Santa Clara	Interstellar Dust	Observations, laboratory work, theory
Whittet (1992)	Dust in the Galactic Environment	Observations, theory
Millar and Williams (1993) Conf. Univ. Manchester	Dust and Chemistry in Astronomy	Laboratory work, theory
Kwok (1993) Conf. Univ. Calgary	Astronomical Infrared Spectroscopy: Future Observational Directions	Observations, laboratory work
Evans (1994)	The Dusty Universe	Observations, theory
Cutri and Latter (1994)	The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds	Observations, theory
Nenner (1994) Meeting in Mont Sainte-Odile	Molecules and Grains in Space	Observations, laboratory work, theory
Greenberg (1995) ASI Conf. Erice	The Cosmic Dust Connection	Observations, laboratory work, solar system solids

Further, in the last decade, the views on the role of dust have considerably changed. The time is finally over in which dust was studied only for the sake of completeness as a component of the interstellar medium (ISM) or merely as a factor falsifying distances and distorting spectral energy distributions. Interstellar dust has turned out to be a ubiquitously active factor not only decisively modifying the physical conditions in the ISM but influencing the whole galactic evolution vigorously. Evolved stars inject newly formed dust grains into the diffuse ISM, where they are involved in many interactive processes with gas, stellar radiation and cosmic rays. Increasing dust extinction prevents stellar radiation from penetrating dense clouds so that they remain cool. Molecules formed at the grain surfaces and/or in the gas are protected against photodissociation and are enriched in the dense clouds. The low gas temperature in such cold clouds favours the occurrence of gravitational instability. In addition, grains carry a significant amount of the electrical charge in dense molecular cloud cores. Therefore, they are important for the interaction between neutral gas, ionized species, and the magnetic field and for the rate of ambipolar diffusion in the star-forming cores. Thus, the most basic process of the galactic evolution, the star formation, is triggered by dust concentration and gas-dust interaction. Star formation is a sink for the dust in the Galaxy, but, on the other hand, the advanced stages of stellar evolution are an essential source of new dust. The modern picture of interstellar dust is a thoroughly evolutionary one. Dust is both subject and agent of galactic evolution.

The cosmic dust consists of several well-distinguished populations. They are typical of the special environments in which they are formed and/or decisively modified. Each population is a multi-component particulate containing grains or grain ingredients of different chemical composition and solid-state structure. The condition of the origin and the subsequent metamorphosis strongly influences the optical properties, the size and shape distributions of the grains, and the grain model at all. There are at least four main populations:

1. Stellar outflow dust (stardust)
2. Dust in the diffuse ISM (interstellar dust)
3. Dust in dense cool clouds (molecular cloud dust)
4. Circumstellar dust around young stellar objects (YSO dust)

There is some evidence for subdivisions of the above main populations as well as for further dust populations. For example, there are two chemical subgroups of stardust around giants: oxygen-rich and carbon-rich dust. Further, there are differences due to the physical conditions of the environment. The dust spectrum of Mira stars shows other features than that of a planetary nebula. Within a molecular cloud, dust grains in photodissociation zones and in the hot star-forming cores have other properties than those in the cold protostellar cores. Circumstellar dust in disks around low-mass YSOs shows properties different from those in envelopes around massive YSOs and intermediate-mass Herbig Ae/Be stars. Dust in disks around main-sequence stars (Vega phenomenon) has special characteristics making it a separate dust population. Probably, this "disk dust" is somehow connected with the formation of planetary systems and, thus, could be closely related to solar system solids. However, a direct comparison with interplanetary dust is not appropriate because the latter was strongly modified in the formation process of the solar system.

The dramatic development of the dust research in the last decade is reflected by a number of comprehensive meetings. The most important ones since the IAU Symposium 135 in 1989 have been listed in Table. 1. It is a primary goal of our review to characterize the populations which we use as the division scheme as clearly as possible and to discuss the processes that are constitutive within a population. A further important goal is to point out consequently the evolutionary characteristics of the galactic dust and to discuss the processes explaining the metamorphosis of the grain material if the grains are conveyed from one environment to another one in the Galaxy and if ISM phase transitions take place.

In Sect. 2, we discuss the stardust sources permanently transforming stellar gas into new dust grains which are injected into the interstellar medium and subjected to the galactic evolution. In Sect. 3, the properties of the dust grains in the diffuse ISM are described, where destruction and recondensation processes of grains or grain components modify the size distribution and the structure of the grains considerably. Section 4 is devoted to the processes changing dust grains in different regions of molecular clouds inclusive in star-forming regions. In Sect. 5, dust grains in the environments around YSOs and main-sequence stars with the Vega phenomenon are discussed.

2 Primary dust sources

2.1 Stellar mass loss and stardust formation

Since about two decades, it has been a generally accepted fact that stellar mass loss represents an important source injecting dust into the interstellar space. In this connection, the term "stardust" was coined (Ney 1977). Temporarily, the conviction among theorists arose that stardust is the dominating source of newly formed dust, but meanwhile formation of volatile dust in dense clouds (see Sect. 4) and growth of refractory dust grains in the diffuse ISM (see Sect. 3) have turned out to be processes of, at least, comparable efficiency.

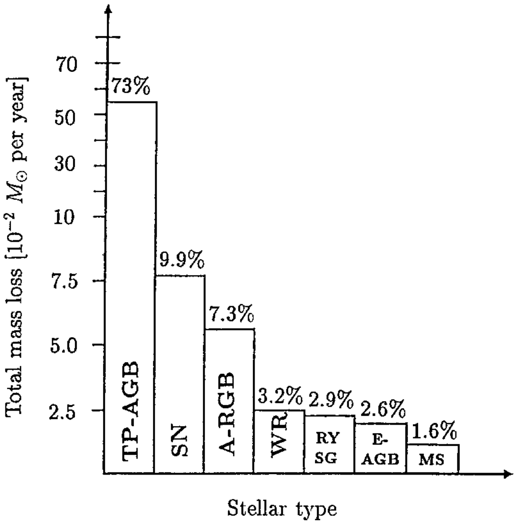

Fig. 1. Total galactic mass loss of various stellar types. *TP-AGB* thermally pulsing AGB stars; *SN* supernovae; *A-RGB* asymptotic red giant branch stars; *WR* Wolf-Rayet stars; *RYSG* red and yellow supergiants; *E-AGB* early AGB stars; *MS* main sequence stars. On top of the columns the relative contribution to the total mass loss is given. After Sedlmayr (1994)

Table 2. Galactic stardust injection rates according to Jones and Tielens (1994)

Sources	Total contribution (10^{-6} $M_\odot$ kpc^{-2} yr^{-1})	
	silicate	carbon
M giants	3	-
C giants	-	2
supergiants	0.2	-
WC stars	-	0.06
planetary nebulae	-	0.04
novae	0.03	0.3
supernovae type Ia	2	0.3
supernovae type II	12	2

About 90% of the stellar mass loss is provided by cool high-luminosity stars, in particular by AGB and post-AGB stars. The remaining 10% is due to planetary nebulae, novae, supernovae, and also to Wolf-Rayet stars. Reviews of observational and theoretical work on stardust were given by Dwek (1986), Bode (1988), Gehrz (1989), Whittet (1989, 1992), and Sedlmayr (1994). In Fig. 1, the total galactic mass loss is plotted vs the types of stellar contributors. In Table 2 the stardust injection rates for the main stardust components, silicates and carbon, are listed (Jones and Tielens 1994).

The dust injection rate of supernovae in Table 1 could be overestimated because the efficiency of dust formation in the environment of supernovae is not known. At any rate, supernovae are the main contributors of elements heavier than carbon to the ISM and, thus, strongly influence the budget of refractory grains in interstellar space. There is some evidence for dust formation in supernova explosion shells, e.g. SN1987A (Wooden et al. 1993), but up to now diagnostic dust features have not been observed (see, however, Timmermann and Larson 1993). According to the estimation by Jones and Tielens (1994) the interstellar dust could be replenished on a time-scale of 2.5×10^9 years.

The identification of stardust grains in primitive meteorites and interplanetary dust particles (IDPs) has opened a direct information source (Anders and Zinner 1993; Ott 1993a,b; Zinner 1995). The isotopic patterns of important elements in these highly-refractory grains are totally different from those of solar system material. They can, however, be interpreted in terms of the current theory of nucleosynthesis in AGB stars and supernovae and, thus, clearly underline the stardust origin. The study of presolar grains in meteorites by the sensitive methods of chemical and mineralogical analytics provides information on some dust species (diamond, silicon carbide, graphite, and corundum grains) and their origin which is unprocurable by astrophysical methods.

Theoretical modelling and astronomical IR spectroscopy have shown that there are two chemical regimes generating basically different "stardust subpopulations" depending on the O/C ratio at the circumstellar formation place. In this context the CO molecule with its exceptional high binding energy of 11.06 eV plays an important role. For O/C$\geq$1 (M-type stars) all carbon present in the gas is oxidized to CO and, thus, no longer available for the formation of solids. The excess oxygen forms refractory solids of oxidic composition, mainly silicates. For stars with O/C$\leq$1 (C-type stars), the excess carbon not consumed by the CO formation is available for the formation of a large number of organic molecules observable in carbon stars (see, e.g., Omont 1991) and for the direct condensation to carbonaceous grains. In this review, we distinguish between "carbon grains" containing only C atoms and "carbonaceous grains" that apart from carbon also contain other atoms. The details of the molecule-solid transition field are not sufficiently understood. Basic principles of dust formation in late-type stellar winds have been worked out by Gail et al. (references in Sedlmayr 1994), Kosaza et al. (Kozasa and Hasegawa 1987), Donn et al. (references in Nuth 1995), Egan and Leung (1995), and Dorfi et al. (references in Höfner et al. 1995). For the quantitative description of the nucleation regime leading to the formation of critical clusters mainly the thermodynamical approach (classical nucleation theory) and to a much smaller extent the approach via chemical kinetics (chemical pathway method) have been used. It is commonly assumed that the main part of nucleation takes place in the temperature range from 1300 to 700 K (Whittet 1992; Sedlmayr 1994). Strong criticism on the use of the classical nucleation theory has been expressed by Nuth and Donn (1983), Donn and Nuth (1985) and by Nuth (1995). They pointed out that because of the non-equilibrium conditions in the stellar atmosphere the distribution of the molecular vibrations strongly deviates from a Boltzmann distribution. This effect stabilizes heteroatomic clusters against collisional dissociation and leads to the fast growth of amorphous, nonstoichiometric refractory grains. Experiments with Mg-SiO and Fe-SiO systems confirmed these conclusions (Nuth and Donn 1983).

The location of the zone of most effective grain formation in the outer atmospheric/circumstellar shell is a matter of debate (Rowan-Robinson and Harris 1982; Tielens 1990a,b). Multi-stage processes are discussed which begin with the nucleation of highly refractory compounds in the innermost part of the circumstellar envelope, whereas the main growth occurs in the cooler outer parts onto these precursor condensates (see, e.g., Frenklach et al. 1989; Whittet 1992; Sedlmayr 1994; Kosaza et al. 1995). Whether the result of the condensation is an amorphous or a crystalline, a monocrystalline or a polycrystalline, a homogeneous or heterogeneous solid depends on the (almost unknown) microphysical timescales in the period of the main condensation (Sedlmayr 1989).

There are interesting exceptions from the described rule that silicates condense in M-type stars and carbonaceous dust in C-type stars. Apparently, S-type stars represent the transition between both chemical regimes (Little-Marenin and Little 1988; Chen and Kwok 1993). Some carbon stars show the silicate emission bands (Little-Marenin 1986; Willems and de Jong 1986; Chan and Kwok 1991; Kwok and Chan 1993). Chan (1993) found that some of these objects are ^{13}C-rich stars (J-type stars). On the other hand, M-type supergiants have been found which show the silicate bands and in addition the SiC band or the so-called Unidentified IR Bands (UIBs) attributed to carbonaceous clusters in the molecular-solid transition field or to hydrogenated amorphous carbon grains (Skinner and Whitmore 1988; Skinner et al. 1990; Sylvester et al. 1994). In the first case, the silicate emission is probably the remnant of the circumstellar shell of the star that originally was a M-type star the photosphere of which was enriched with carbon as the result of the carbon dredge up by thermal pulses (Willems and de Jong 1988). In the second case, chromospheric UV radiation could have dissociated CO molecules and, thus, opened a source of carbon available to chemical reactions and to condensation (Sylvester et al. 1994). However, it cannot be fully excluded that the effect is due to unresolved binaries.

2.2 Oxidic stardust

Vibrational bands of silicates positioned at about 10 and 18 μm have been the first bands reliably attributed to well-known bonds (for reviewing the history of their detection see Gürtler et al. 1989). The most comprehensive compilation of silicate stardust spectra is the IRAS LRS catalogue edited by Olnon and Raimond (1986) containing 1808 objects with the 10- and 18-μm bands in emission and 297 objects with the 10-μm band in absorption. Most of the emission sources are dusty envelopes around late-type giants, however, some of them are connected with young stars (T Tauri, Herbig Ae/Be stars). From the absorption sources only very cool AGB stars with optically thick envelopes (Bedijn 1987; Omont 1993) belong to the stardust population, the other ones are mainly massive young stellar objects (YSOs) deeply embedded in dust envelopes (Henning et al. 1984; Gürtler et al. 1985; see also Sect. 5). In the outer parts of optically thick envelopes around AGB stars even volatile dust grains ("ices") are formed (see, e.g., Whittet 1989; Omont et al. 1990).

Inspecting the silicate bands of the numerous IRAS LRS catalogue sources has revealed significant intrinsic differences of the silicate band profiles and challenged the investigators to introduce classification schemes (see, e.g., Little-Marenin and Little 1988, 1990; Simpson 1991). This clearly demonstrates that there is a considerable mineralogical diversity (Tielens 1990a) in circumstellar silicate dust and that it is far more complex than previously assumed (Goebel et al. 1994). At present, the discussion of the "mineralogical diversity" is still in the phase of articulating the questions rather than to give reliable answers (see Jäger et al. 1994).

Here, we point to a restricted meaning of the mineralogical term "silicate". In our astrophysical context it only means that the grain material contains silicon-oxygen bonds in such a spatial arrangement that in addition to Si-O stretching vibrations (10-μm band) also bending vibrations become possible and manifest themselves by the appearance of a second band at 18 μm. The broad structureless profiles of these bands point to the total loss of long-range order so that the degree of disorder (amorphousness) is commonly compared with that of silicate glasses (Dorschner and Henning 1986; Dorschner et al. 1989; Jäger et al. 1994; Dorschner et al. 1995). Statements concerning the solid-state structure of cosmic silicates are mainly based on IR spectroscopy. Simulation experiments that study the structure via X-ray measurements are rare cases (see, e.g., Thompson et al. 1995).

Since silicates do not exist in the gas phase, their formation in circumstellar envelopes mainly rests on SiO and/or MgO clusters chemisorbing gas components (Mg, Fe, SiO, H_2O). As the grains form under non-equilibrium conditions, in contrast to glasses, unequilibrated components, nonstoichiometric ratios (O deficiency: not all of the Si ions form perfect SiO_4 tetrahedra) and dangling bonds should be expected (Nuth and Hecht 1990; Nuth 1995).

Up to now, silicate grains with a typical AGB star isotope signature have not been detected in primitive solar system solids. However, Bradley (1994) found nonstoichiometric grains of silicate glasses with depletions of magnesium and silicon relative to oxygen and inclusions of iron-nickel metal and iron sulfides (GEMS=*G*lasses with *E*mbedded *M*etal and *S*ulfide) and other indications of pre-accretional origin. GEMS are a special subgroup of polyphase grains occurring in most interplanetary dust particles of cometary origin (synonymous designations in the mineralogical literature are "tar balls", "granular units", and "unequilibrated aggregates"). GEMS probably represent interstellar silicate grains. Against this new background, Goebel et al. (1994) suggest to discuss anew the Ca-Al inclusions (CAI) of carbonaceous chondrites. When the CAI of the Allende meteorite were detected (see also Clayton's 1992 reflections on the "chemical memory"), the existence of unchanged interstellar dust components in solar system solids was not imaginable.

Apart from silicates, metal oxide grains can be expected in oxygen-rich stars (Rietmeijer 1992; Begemann et al. 1995a; Henning et al. 1995a). The latter authors discussed MgO, FeO, $Mg_xFe_{1-x}O$ as stardust components and measured the optical constants of laboratory analogues. Objects with weak or lacking 10 μm bands, but showing strong bands in the range from 17-25 μm are suspected to contain such oxide grains. Good candidates are the IRAS LRS catalogue objects of the class λ as defined by Goebel et al. (1989). The only oxide definitely identified by an observed band in the spectra of Mira stars is Al_2O_3 (Vardya et al. 1986; Onaka et al. 1989; Stencel et al. 1990). The coexistence of oxide with silicate grains has got some substantial support by the recent detection of presolar corundum (Al_2O_3) and spinel ($MgAl_2O_4$) grains in meteorites (Nittler et al. 1994, 1995). Such highly refractory oxides that nucleate at much higher temperatures than silicates could be the forerunners and trigger the massive formation of the latter (Stencel et al. 1990). The possible role of Al_2O_3 in astronomical environments was discussed by Koike et al. (1995) and lead them to determine optical constants for the wavelength range 200 nm to 400 μm. A similar effort, but for amorphous Al_2O_3 was carried out by Begemann et al. (1995b).

2.3 Carbonaceous stardust

Pure carbon dust should be expected only in hydrogen-deficient stars. As normal carbon stars are hydrogen-rich, H atoms must be the most important hetero-atoms of the carbonaceous dust. Hydrogen-containing molecules, e.g., acetylene (C_2H_2) and polyynes are assumed to be the molecular base for the nucleation of carbonaceous solids in these stars (Tielens 1990b; Howard et al. 1991; Whittet 1992; Sedlmayr 1994).

Even in hydrogen-deficient stars the solids are expected to be amorphous forms of carbon rather than crystalline ones (diamond, graphite, fullerite) because the condensation occurs under non-equilibrium conditions. All attempts to detect crystalline graphite in carbon-rich stars failed (Draine 1984; Glasse et al. 1986). Amorphous carbon (a-C) is a heterogeneous mixture of sp^3 and sp^2, and somtimes even sp^1 bonded carbon species. It contains randomly oriented rings or aromatic islands (comparable to finite graphite planes or the polymerized rings in the polycyclic aromatic hydrocarbons) connected with each other by sp^3 bonds. The sp^2/sp^3 ratio is an important parameter characterizing a-C and influencing its optical properties (Duley 1993; Preibisch et al. 1993). The a-C types vary from micrographitic soot consisting of irregularly arranged tiny piles of sp^2 bonded aromatic planes to diamond-like carbon containing large domains with sp^3 bonds. This structural variety is reflected by a multitude of different laboratory analogues produced by combustion of hydrocarbons, by carbon vaporization in arcs or by laser pulses, and by recondensation of sputtered carbon (Bussoletti and Colangeli 1990; Krätschmer 1993; Duley 1993).

One important type of hydrogen-deficient stars are WC stars. The large IR excesses of these stars are thought to be due to carbon grains condensed in their strong stellar wind (Williams et al. 1987). This interpretation has been supported by the detection of an emission band at 7.7 μm (Cohen et al. 1989) which is attributed to aromatic C-C stretching vibrations.

IUE observations (Holm et al. 1982) of the H-deficient R CrB variables, the irregular lightfalls of which are caused by the sudden formation of clouds of carbon dust in their envelopes, have confirmed the above expectations. In their spectra a prominent UV emission band at 240-250 nm was detected and attributed to amorphous carbon grains (Hecht 1991). This band is clearly different from the extinction bump at 217.5 nm commonly attributed to surface plasmons in nanometre-sized graphite grains (cf. Draine 1989) or graphitic spheres ("carbon onions" or "multi-shell fullerenes", cf. de Heer & Ugarte 1993; Ugarte 1993, 1995). Generally, laboratory experiments showed that soot grains produced in an inert H-deficient atmosphere have an absorption peak at 240 to 260 nm instead of the well-known interstellar extinction bump at 217.5 nm (Blanco et al. 1991; Jäger 1994).

Soot grains produced by the same laboratory techniques in a hydrogen atmosphere lose this characteristic feature (Blanco et al. 1991). However, a UV feature appears if such hydrogenated carbon grains are annealed. Blanco et al. (1993) found broad bands between 205 and 250 nm depending on the temperature and the duration of the annealing. The common conclusion is that stardust grains should consist of hydrogenated amorphous carbon (HAC; Jones et al. 1990; Duley 1993). A schematic illustration of the carbon atom bonding in HAC is given in Fig. 2. In interstellar space dehydrogenation and graphitization of HAC occurs transforming the HAC grains to graphitic grains with the surface resonance at 217.5 nm (for details see Sect. 3.3.2). In R CrB stars, because of their hydrogen deficiency, grains of soot-like amorphous carbon without hydrogenation are formed. Even if this very simple picture needs experimental and astrophysical confirmation, the experiments by Blanco et al. (1991, 1993) and Mennella et al. (1995a,b), at any case, underline that dehydrogenation and graphitization predicted by Hecht (1986) and Sorrell (1990, 1991) play an important role in understanding the spectral difference between stellar and interstellar carbon grains.

The detection of presolar crystalline carbon (and SiC) phases in primitive solar system solids puts some new accents to the discussion on carbonaceous stardust. The most abundant of these phases (400 ppm) consists of nanometre-sized grains of face-centred cubic (fcc) diamond (Lewis et al. 1987) which have been detected in all classes of unmetamorphosed chondrites (Huss 1990; Huss and Lewis 1995). From the

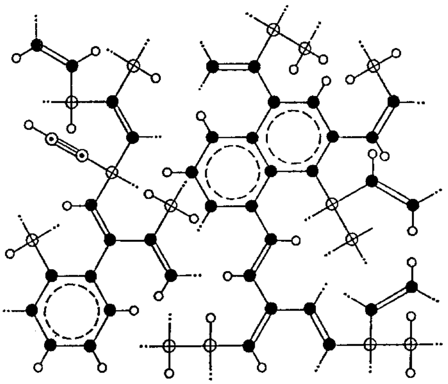

Fig. 2. Schematic representation illustrating types of carbon atom bonding in HAC. *Circled crosses* sp^3; *full circles* sp^2; *circled dots* sp; *open circles* hydrogen atoms. After Jones et al. (1990)

size, the designation "nanodiamonds" was derived which, meanwhile, has replaced the first designation "microdiamonds". Before their final identification with diamonds this phase was well-known as the carrier of a striking anomaly of xenon isotopes (Xe-HL anomaly) designated as C_δ.

The density of the meteoritic diamonds turned out to be 30% lower than that of terrestrial diamonds. They contain a relatively high hydrogen content (10-40 atom%) considerably enriched with deuterium (δD=180-284; Carey et al. 1987; Virag et al. 1989) and a nitrogen content of 0.3 to 1.2 mass % (Russell et al. 1991). Transmission electron microscopic (TEM) studies and electron energy loss spectra suggested the presence of amorphous carbon material containing π-bonded carbon in addition to the σ-bonded diamond. From this findings Bernatowicz et al. (1990) suggested an additional carbon component consisting of hydrogen-rich HAC somehow connected with the nanodiamonds

A consequence of these small sizes of the meteoritic diamonds is that a considerable fraction of the carbon atoms are surface atoms. Chemical groups bonded to these atoms strongly modify the optical properties in the IR region (Lewis et al. 1989; Mutschke et al. 1995; see Fig. 3). If some of these prominent IR bands are pristine properties and if the diamonds are a sufficiently abundant component of the interstellar carbon dust, the bands should be detectable, e.g., in the spectra expected from the Infrared Space Observatory ISO and could, thus, form the base for the future observational investigation of the possible interstellar diamond dust.

The origin of the nanodiamonds is less clear than that of other presolar phases. Diamond condensation in carbon stars by chemical vapour deposition (CVD) was originally suggested by Saslaw and Gaustad (1969) and was restored to life by Lewis et al. (1987) after the identification of the C_δ carrier with diamonds. Jørgensen (1988) considered the formation via CVD-like processes in the outflows of carbon-rich giants which are members of binary stars, the other component of which exploded as supernova (type I) and implanted its isotopic pattern into the diamonds.

Presolar graphite grains are found in meteorites with only about 1 ppm (Anders and Zinner 1993; Ott 1993a, b). In most cases, they are micrometre-sized onion-like carbon spheres composed of discontinuous concentric graphite layers. Between these layers crystallites of other refractory stellar solids, e.g. TiC, have been found documenting the growth process in a medium where also other grain seeds were

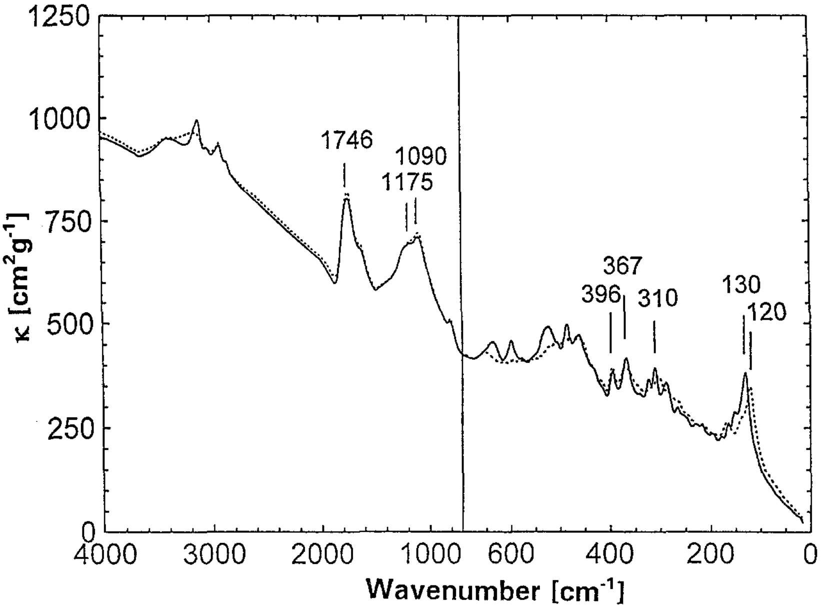

Fig. 3. Mass absorption coefficient κ of presolar diamond grains extracted from the Murchison meteorite, derived from transmission spectra in the spectral range 2.5-500 μm for sample temperatures of 10 K (*solid line*) and about 300 K (*dotted line*). The absorption bands are due to chemical groups at the grains' surfaces. Some of these features are suspicious to be artefacts produced during the chemical extraction procedure. The strong FIR band at 130 cm^{-1} seems to be an intrinsic interstellar diamond feature that could serve for the future observational investigation of interstellar diamond dust. After Mutschke et al. (1995)

present (Bernatowicz et al. 1991). A detailed study of more than 100 graphite grains isolated from the Murchison meteorite resulted in the detection of a low-density (1.65-1.72 g cm^{-3}) and a heavier graphite fraction (2.15-2.20 g cm^{-3}) showing different isotopic patterns (Amari et al. 1995). There are indications that some of the high-density graphite grains could come from AGB stars, whereas most of the low-density grains should originate from massive stars (Wolf-Rayet stars, type II supernovae). It is, however, not clear whether the dominant graphitic structure of these presolar grains is the original one or has come about through interstellar modification (Ogmen and Duley 1988). Laboratory experiments with nanometre-sized carbon arc soot particles subjected to strong electron beam irradiation or simply to annealing have shown that a reorganization of the structure occurs and preferentially spherical particles form (Ugarte 1992; de Heer and Ugarte 1993). Even if these nanometer-sized carbon onions are two orders of magnitude smaller and of much more regular structure than the meteoritic spheres these experiments point to the fact that at least in the size range of large carbon clusters, the spherical graphitic form is the most stable carbon allotrope (Ugarte 1993).

Apart from HAC another form of carbonaceous material has attracted great attention: polycyclic aromatic hydrocarbons (PAH; Allamandola et al. 1987; Puget and Léger 1989; Cherchneff and Barker 1992). Originally, PAHs as possible dust component were suggested by Donn (1968). Contrary to HAC which is a solid, PAHs are planar molecules consisting of polymerized hexagonal rings with hydrogen atoms at their outer rim. Large PAHs can be considered as regularly structured clusters of

sp^2-bonded carbon with hydrogen at their edges. Thus, they are structures in the transition field from molecules to solids. A strong impact to the study of PAHs came from the indications for the occurrence of very small particles (especially by the discovery of the IRAS IR cirrus clouds, see Sect. 3.2.2.) and by the detection of the UIBs. In the last two decades, numerous such bands have been found which can be classified into three groups (Sellgren 1990): main features (3.3, 6.2, 7.7, 8.6, 11.3 μm) ; weak features (3.40, 3.46, 3.52, 3.57, 5.2, 5.7, 6.9, 11.9, 12.7 μm); broad features or plateaus (3.2-3.6, 6-9, 11-13 μm). These bands occur in the spectra of very different objects which in many cases are definitely carbon-rich and which are characterized by an enhanced UV and/or optical radiation field: planetary nebulae, novae, Wolf-Rayet stars. In carbon-rich planetary nebulae, the strengths of some UIBs are well-correlated with the C/O ratio (Sellgren 1990). UIBs also occur in interstellar clouds, H II regions (star-forming regions), Herbig Ae stars, reflection nebulae, and probably also as large-scale galactic emission (see Sects. 3 and 5).

Laboratory analogue experiments with carbonaceous material containing major quantities of aromatically bonded carbon, e.g., coals, coal tar, aromatic char, HAC, "quenched carbon composites" (QCC) , and with special or mixtures of different PAHs show indeed spectra with striking resemblence to the UIBs. A detailed report of laboratory analogue measurements was included in the paper by Sellgren (1994), the assignment of UIBs to special PAH vibrations can be found in the paper by Allamandola et al. 1989). Generally, the observed band widths of the UIBs are explained by the number of carbon atoms in the PAHs (see Allamandola et al. 1989). The pros and cons of the PAH hypothesis have been discussed in detail in the IAU symposium No. 135 (Allamandola and Tielens 1989) and, more recently, in the conference "Molecules and Grains in Space" (Nenner 1994). Even if the identification problem of the UIBs has not yet been finally settled, some authors (see, e.g., Jourdain de Muizon 1993) already definitively speak of "PAH" bands if they mean UIBs.

Aromatic rings and their polymerization products (with and without hydrogen saturation) are discussed to be formed in carbon stars, in carbon-rich Wolf-Rayet stars, in R CrB stars, in supernovae, and in S-type stars (Allamandola et al. 1989; Tielens 1990b; Cherchneff and Barker 1992; Sylvester et al. 1994; Sedlmayr 1994). Experimental studies suggest that higher PAHs are stable in the diffuse ISM. They should, however, be rapidly destroyed after accretion on grains in dense clouds (Mendoza-Goméz et al. 1995). This should limit their lifetime in space to $\leq 5\times10^7$ years and, thus, points to a survival problem of this material. Evidence for PAH destruction at ionization fronts has been presented by Giard et al. (1994b).

A general problem is whether or not aromatic compounds remain as molecules (PAHs in the strict verbal sense) in the diffuse ISM or form amorphous grains (a-C, HAC). In the latter case the aromatic islands contained in these solids could be responsible for the UIB emission (Duley 1989). This model assumes that weakly linked islands in the solid undergo large temperature excursions. Laboratory experiments with QCC seem to underline these conclusions (see, e.g., Sakata and Wada 1989). However, recent experimental and theoretical studies (Boutin et al. 1995) contradict the island model.

Observational evidence in favour of a molecular origin of the 3.3 μm band, at least, was found by Geballe et al. (1994) who detected a band at 1.67 μm in the planetary nebula IRAS 21282 +5050, a strong UIB emitter, and considered it as the overtone (v=2-0) of the 3.3 μm band. If this assignment is correct, then the high excitation necessary for the emission in this band would indeed indicate that the emission is by free molecules rather than by aromatic islands enclosed in a carbon solid. Further, the intensity ratio of the 2-0 band to the 1-0 band would imply that the emitting species should contain about 60 carbon atoms.

For the nucleation of carbon grains different ways have been studied. For example, the grain formation can be initiated by PAH molecules (Tielens 1990b; Sedlmayr 1994 and references therein) or the nucleation is opened by SiC (Frenklach et al. 1989; Lorenz-Martins and Lefèvre 1994; Kozasa et al. 1995). Many carbon stars show a strong emission band at 11.3 μm whose band strength is tightly correlated with the star's mass loss rate (Skinner and Whitmore 1988). It has been assigned to Si-C vibrations of silicon carbide grains. Up to now, more than 600 stars showing the SiC band in emission have been found, but only one object, GL 3068, with the 11.3 μm band in absorption was detected (Jones et al. 1978). The observed 11.3 μm bands do not show the shoulders on both band wings typical of laboratory spectra of crystalline SiC grains and being due to the longitudinal and transversal phonon resonances (Dorschner et al. 1977; Friedemann et al. 1981; Borghesi et al. 1983). Baron et al. (1987) considered the absence of the shoulders as a sign of amorphousness. New laboratory measurements on amorphous SiC produced by sol-gel reactions (Begemann et al. 1995c) confirm this conclusion.

Attempts to detect interstellar SiC absorption failed (Whittet et al. 1990). At present, it is not clear, how this enigmatic behaviour could be explained. Whittet et al. (1990) proposed that SiC could be effectively oxidized in interstellar space. It could, however, be possible that already in the stellar outflow the small SiC grains get surrounded by thick carbon mantles so that the 11.3 μm band vanishes (see Kozasa et al. 1995). This latter explanation must, however, be reconciled with the fact that micrometre-sized SiC grains, which are euhedral crystallites of β SiC as well as aggregates of smaller subgrains, have been found in primitive meteorites. Extensive isotopic studies (Hoppe et al. 1994; Lewis et al. 1994) confirmed that AGB stars are the most likely source of these grains. There are, however, several subtypes pointing to different sources (supernovae, novae, WC stars; see, e.g., Amari et al. 1992). In any case, a stellar origin in indicated. These presolar SiC grains are more abundant than graphite onions, but much less abundant than nanodiamonds. The mass ratio of graphite:SiC:nanodiamonds corresponds to 1:5:400 (Anders and Zinner 1993; Ott 1993a,b). The large diameters suggest that only the large-size fraction of these grains can survive the stay in the interstellar environment. In agreement with their low abundance in the meteorites SiC has not been detected in the mass spectra of comet Halley dust (Jessberger 1994).

The reducing conditions present in carbon stars could also be favourable for the condensation of other oxygen-free solids, e.g., sulfides which were discussed in connection with unidentified emission features at 30 and 21 μm wavelength. The extremely strong 30 μm band observed in carbon-rich AGB stars, protoplanetary nebulae and planetary nebulae (see, e.g., Cox 1993; Omont et al. 1995 and literature therein) has been identified with the vibrational band of MgS (Goebel and Moseley 1985; Nuth et al. 1985). The discussion was extended to the formation of Mg-Fe sulfides in carbon stars by Mutschke et al. 1994 (see Fig. 4). Because of chemical instability under oxidizing conditions stardust MgS has no chance to survive the passage through the interstellar space. However, iron-rich sulfides which are much more stable under these conditions could be expected to occur both as interstellar dust component and as a possible presolar ingredient in primitive solar system solids (Dorschner and Schulze 1993; Begemann et al. 1994). If the sulfide-bearing GEMS phase found by Bradley (1994) in interplanetary dust particles is indeed presolar dust, these expectations would be confirmed.

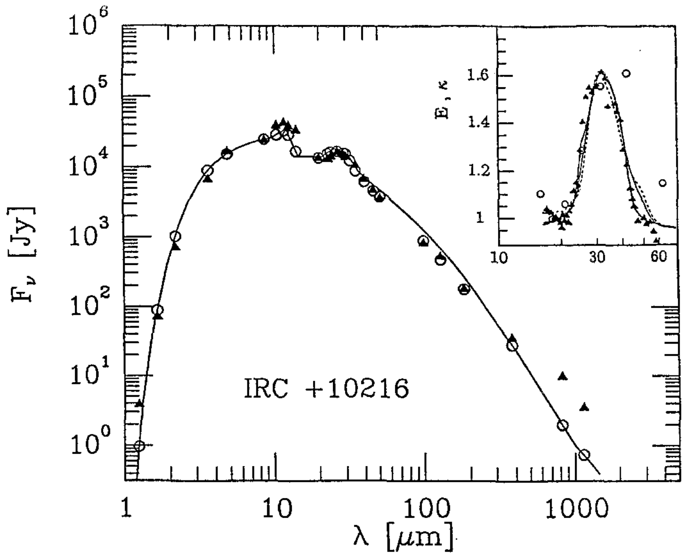

Fig. 4. Spectrum of the carbon star IRC +10 216 with special regard of the 30-μm band. *Triangles* and *open circles* are observed and model fluxes, respectively. The profile of the 30-μm band (*inserted graph*) can be excellently represented by Mg-rich sulfide particles. The normalized observational data $E(\lambda)$ (*triangles*) have been taken from Cox (1993). The profile curves $\kappa(\lambda)$ have been calculated for a continuous distribution of ellipsoids (CDE) using laboratory data measured by Mutschke et al. (1994) for $Mg_{1-x}Fe_xS$ with x=0.1 (*heavy solid line*), x=0.25 (*thin solid line*), and x=0.5 (*dashed line*). *Open circles* are MgS data by Nuth et al. (1985). After Begemann et al. (1994)

In the spectra of several carbon-rich protoplanetary nebulae a strong emission band at 21 μm has been detected (Kwok et al. 1989, 1993). In the IRAS LRS database further objects that apparently show indications for this band have been found (Henning et al. 1995b), but these findings need further confirmation. Oudmaijer and de Winter (1995) pointed out that in case of extended sources such as H II regions IRAS LRS spectra show a spurious indication for the presence of a 21-μm feature.

Omont et al. (1994) concluded that the occurrence of this band is limited to the short-lived PPN phase and that its carrier could be a transient species related to the extreme conditions to which dust is exposed during this phase. Based on laboratory data by Nuth et al. (1985), Goebel (1993) proposed SiS_2 grains as the carrier of this band. The identification of UIBs in the spectra of these sources (Buss et al. 1990) points to the possibility that the 21 μm band could be somehow connected with carbonaceous grains (HAC, PAH). Although protoplanetary nebulae with strong 21 μm bands also show the 30 μm band, there is apparently no correlation between the band strengths.

3 Dust in the diffuse interstellar medium

3.1 The diffuse ISM conception

3.1.1 The three-phase model of the diffuse ISM

The diffuse interstellar matter consists of dusty gas clouds embedded in a thin hot ionized matter (HIM in Table 3) coming from supernova remnants. For the clouds a

Table 3. Properties of diffuse ISM. The meaning of the symbols is: *CNM* cold neutral medium; *WNM* warm neutral medium; *WIM* warm ionized medium; *HIM* hot ionized medium

Parameter	Value	Reference
Volume filling factors of the model	CNM: 0.025; WNM: 0.15 WIM: 0.23; HIM: 0.6	McKee and Ostriker (1977), Shull (1987)
Average cloud radii	WNM: 1.6 pc; WIM: 2.1 pc	
Gas densities of the model	CNM: 42 cm^{-3}; WNM: 0.37 cm^{-3} WIM: 0.25 cm^{-3}; HIM: 0.0035 cm^{-3}	
Gas temperatures	CNM: 80 K; WNM: 8000 K WIM: 8000 K; HIM: 450000 K	
Mean rate of visual extinction near galactic plane	$\langle A_V/l \rangle$ = 1.8 mag per kpc	Whittet (1992)
Average dust density	1.8×10^{-26} gcm^{-3}	Whittet (1992)
Dust temperature in CNM	T=18±2 K	Draine (1994)
Extinction per H-Atom	$A_V/N(H)$ = 5.3 10^{-22} mag per H column density	Bohlin et al. (1978)
Slope of extinction law	average: $A_V/E(B-V)$=3.1 dense clouds: $A_V/E(B-V)$=4...6	Massa and Savage (1989)
Parameters of the UV bump	λ_0=217.5 ± 1 nm $FWHM$ = 48 ± 12nm	Fitzpatrick and Massa (1986)
Major dust components	carbon (microdiamonds, graphitic C), refractory organics, silicates, oxides	
Strength of silicate bands	GC : $\tau(9.7)/A_V$=0.11 Cyg OB 2 #12: $\tau(9.7)/A_V$=0.06 GC: $\tau(19)/A_V$=0.07	Aitken (1989) Adamson et al. (1990) McCarthy et al. (1980)
Strength of the 3.4 μm band	GC IRS 7: $\tau(3.4)/A_V$=0.007 Cyg OB 2 #12: $\tau(3.4)/A_V$=0.003 Lyngå8 IRS3: $\tau(3.4)/A_V$=0.004	McFadzean et al. (1989) Adamson et al. (1990) Tapia et al. (1989)

theoretical three-phase model was proposed by McKee and Ostriker (1977, for short MO model), in which supernovae are the dominating energy input sources. The MO model proposes spherical clouds with two neutral phases:
1. cold cloud cores (cold neutral matter, CNM),
2. warm neutral envelopes (warm neutral matter, WNM).
Both phases represent H I regions; atoms heavier than He with low ionization thresholds are ionized by the interstellar radiation field that is also responsible for the hydrogen dissociation. The neutral components are surrounded by warm ionized outskirts (warm ionized matter, WIM, H II regions). The MO model data are listed in Table 3; for a review of successes and discrepancies of this model see Shull (1987).

The spherical clouds of the MO model are a strong idealization of the reality. Radioastronomical HI observations and studies of UV absorption lines reveal cool clumps (T=30-80K, n(HI)=20-50 cm^{-3}) embedded in sheet- and filament-like H I structures ($T \geq$500K). The surrounding warm H I gas has temperatures of 5000-8000K (Heiles and Kulkarni, 1987). Contrary to the MO model assumptions, H I observations indicate that 30-40 % (per mass) are WNM instead of only 2 % proposed by McKee and Ostriker (1977). Further, photoionization by hot stars has to be considered as an additional energy source.

3.1.2 The local ISM in the solar neighbourhood

A special test field for understanding distribution and kinematics of and the physical conditions within the diffuse ISM is the solar neighbourhood, the "local interstellar medium" (LISM, Crutcher 1982). The analysis of interstellar absorption lines showed that the LISM within 30 pc of the Sun is an array of clouds with different radial velocities that show properties comparable to those of the WNM component of the MO model. These clouds are apparently embedded in the "local bubble" of supernova remnant plasma (Slavin 1989). The "local interstellar cloud" detected by Lallement and Bertin (1992) and confirmed by further observations (Bertin et al. 1993) apparently surrounds the solar heliosphere and is moving past the Sun with about 26 kms^{-1}. Its gas temperature amounts to 7000 K and the Ca depletion of -1.6 points to the presence of dust and suggests a hydrogen density of 0.05 to 0.1 cm^{-3} in this cloud. These values are in agreement with H I measurements within 5-10 pc (Crutcher 1982).

Another possibility to investigate the ISM in the solar vicinity is offered by the statistical analysis of the patchy distribution of interstellar extinction. This classical method was repeatedly applied and led to the knowledge of the three-dimensional dust distribution and to the identification of individual dust clouds within some hundred pc from the Sun (see, e.g., Knude 1984; Ducati 1986 and references therein). In some cases, polarization data have been included into these statistical investigations (see, e.g., Tinbergen 1982). The individual clouds with visual extinctions A_V=0.05 to 0.10 mag correspond to the CNM cores of the "MO clouds", whereas the extinction of the WNM+WIM layer of a MO cloud is much too small to be detectable as an individual cloud. For the LISM in the range of the above gas observations extremely low visual extinction rates of about 6 10^{-5} mag per pc have been estimated (Knude 1979; Tinbergen 1982). From this value, an average dust density in the local interstellar cloud is obtained which is smaller by a factor of about 30 than the average dust density in the galactic plane (cf. Table 3). Knude (1984) derived a cloud number density within 75-100 pc from the Sun of 4.4×10^{-4} clouds pc^{-3} with a volume filling factor of 0.02. From this an average cloud diameter of 4 pc results. Within 500 pc, Ducati (1986) found both individual clouds (average diameter 6 pc) and cloud complexes (diameter $\approx$ 100 pc) yielding an average visual extinction rate over 500 pc of 7.6×10^{-4} mag per pc which is only by a factor of 2.3 below the mean interstellar value.

Interstellar grains with sufficiently low charge-to-mass ratio can penetrate the heliopause and enter the solar system. The successful detection of these passing interstellar grains by the Ulysses dust detector (Grün et al. 1993) has opened a direct way to measure the local dust density. The measured interstellar dust flux is 1.5×10^{-8} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with a mean grain mass of 3×10^{-13} g (Baguhl and Grün 1995). With the heliocentric velocity 26 km s^{-1} of the local interstellar cloud (Bertin et al. 1993), a local dust density of 1.7×10^{-27} g cm^{-3} is obtained from the Ulysses dust flux. This value is larger than the density estimate due to the data by Knude (1979) and Tinbergen (1982). It is, however, by a factor of ten smaller than the average interstellar dust density (cf. Table 3) and also smaller than the average density derived by Ducati (1986) for the solar neighbourhood within 500 pc. Since the Ulysses detector registered grains with masses $\geq 4\times10^{-15}$ g, the real dust density in the local cloud should be somewhat larger depending on the size distribution function of the grains. In any case, the Ulysses flux measurements are in reasonable agreement with the expectations (Draine 1994). However, the mean mass of the detected grains is somewhat larger than expected.

3.2 Observations of dust in diffuse clouds

Direct evidence on physical and chemical properties of the diffuse cloud dust is mainly connected with the following observational phenomena:

1. extinction curve and absorption features,
2. scattering, luminescence, and thermal emission
3. polarization.

The observed properties which will be presented in this section form the base on which most of the currently discussed dust models of the diffuse ISM rest. Additional viewpoints offering indirect evidence for certain dust properties, e.g., the interstellar depletion pattern, will be treated in the following section discussing the dust-modifying processes in the diffuse ISM.

3.2.1 Extinction curve and absorption features

Interstellar extinction responsible for the attenuation and reddening of starlight has been studied in great detail for a large number of lines of sight in the Galaxy. Reviews have been published by Massa and Savage (1989), Mathis (1990), Mathis (1993), and Cardelli (1994). In the UV, the extinction curves clearly show variations along various lines of sight. A basic observational parameter of the extinction curve is

$$R = \frac{A_V}{E(B-V)}, \tag{1}$$

with A_V the total extinction in the V band and $E(B-V)$ the colour excess in the UBV photometric system. For the diffuse ISM, R has the approximately constant value R=3.1, whereas dense clouds and star-forming regions show much larger values (see Sect. 4.1.). The mean slope of $A(\lambda)/A_V$ plotted against R^{-1} has been fitted by Cardelli et al. (1988, 1989) with an empirical expression in the form $a(\lambda)+b(\lambda)R^{-1}$, wherein a and b are analytical functions. This parameterized representation provides the mean extinction curve for any given R (Fig. 5). Martin & Whittet (1990) showed that longward of about 1 μm up to 5 μm the extinction follows a universal wavelength dependence:

$$A(\lambda) \propto \lambda^{-1.8}. \tag{2}$$

Discrete absorption bands are superimposed on the continuous interstellar extinction. By far the strongest one is the UV bump, a prominent solid-state band at 217.5 nm, which was commonly fitted by a classical dispersion or Lorentz profile (see, e.g., Dorschner et al. 1984 and references therein). In the frame of their parameterization, Fitzpatrick and Massa (1986, 1990) reached a somewhat better representation using a slight variation on the Lorentz profile which they referred to as "Drude profile". The band profile was superimposed on a λ^{-1} background. The most noteworthy property of the 217.5-nm band is its invariant position and the relatively large scatter of the FWHM along various lines of sight (see Table 3). Using the parameterization ansatz by Fitzpatrick and Massa (1990), Jenniskens and Greenberg (1993) discussed the dependence of the parameters on the environment, including that of the 217.5-nm feature, for 115 lines of sight. They confirmed the systematic decrease of the linear slope of the visual extinction curve in dense regions. The λ 217.5-nm feature is, however, not

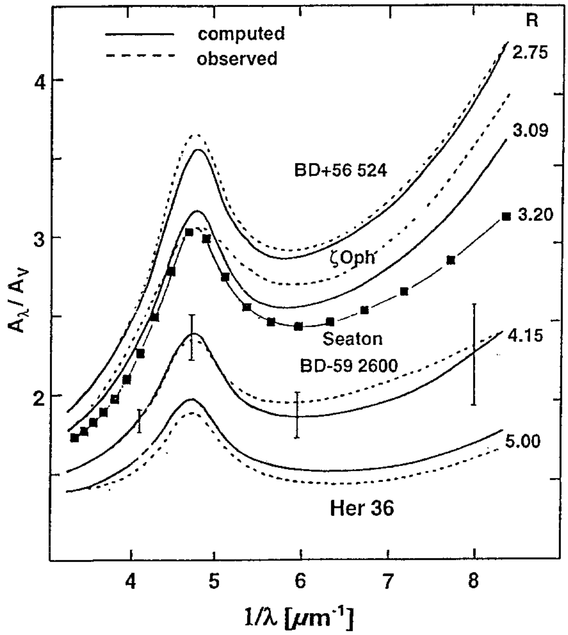

Fig. 5. Normalized extinction curves in the UV computed for several values of R according to the ansatz by Cardelli et al. (1988) are compared with observations. The curve with R=3.20 gives an excellent representation of the standard extinction curve determined by Seaton (1979). The error *bars* on the curve for R=4.15 are the general r.m.s. deviations from the parameterization ansatz. After Cardelli et al. (1988)

reduced in dense media, but in H II regions its strength decreases with increasing radiation field. The authors conclude that this effect should be due to destruction of the λ 217.5-nm band carrier rather than to sticking to big grains. The non-linear rise in the FUV does, however, not show clear correlations with environmental parameters.

In a strict sense, the λ 217.5-nm band carrier has not yet been identified. The numerous identification proposals have been critically reviewed by Draine (1989) who concluded that graphite is the strongest candidate. Up to now, the identification with graphitic carbon corresponds to the general conviction in the dust researchers' community. Recently, Mathis (1994) explained the FWHM variations by differently thick mantles of PAHs on graphite grains. However, Draine and Malhotra (1993) pointed out that the observed profile variations cannot be understood by grain size, shape, clumping and manteling effects alone, but require intrinsic variations of the dielectric properties by impurities, crystallinity variations and/or surface effects.

In the visual and the NIR, a great number of relatively inconspicuous absorption bands that form a kind of fine-structure of the extinction curve and must be somehow related to the diffuse cloud medium still resists identification. Up to now, about 200 of these so-called diffuse interstellar bands (DIBs) in the wavelength range from 400 to 1300 nm are known (Jenniskens and Désert 1993). The strongest DIB is that at 443 nm with a FWHM of 2 nm. Even if the DIBs are clearly connected with the diffuse ISM there is no clear evidence that they are a dust phenomenon at all. At present, PAHs or carbon-chain molecules are discussed as the most promising band carriers (Salama and Allamandola 1992, 1993; Freivogel et al. 1994) The recent state of the discussion on this unsolved spectroscopic problem is summarized in Herbig (1995), the conference book "The Diffuse Interstellar Bands" (Tielens and Snow 1995), and the panel discussion on possible carriers of unidentified spectra (Lequeux 1994).

In the IR spectra of some intrinsically bright stars which are heavily obscured, but which are neither identical with deeply embedded YSOs nor have optically thick circumstellar envelopes, strong absorption bands have been found at the wavelengths 3.0, 3.4, 9.7, and 18.7 μm. With the exception of the broad band at 3.0 μm observed only in some Galactic Centre (GC) sources, these features are probably due to dust in the diffuse ISM. The band at 3.0 μm seems to be a local GC dust characteristic due to O-H stretching vibrations (McFadzean et al. 1989; Pendleton et al. 1994). Its profile is strikingly different from the YSO ice bands as well as from ice bands detected in optically thick circumstellar shells.

The 3.4-μm band has been observed in several IR sources in the GC region, in the heavily obscured "hypergiant" Cyg OB 2 #12, in some supergiants, and in some Wolf-Rayet stars of the types WC9 and WC10 (McFadzean et al. 1989; Adamson et al. 1990; Sandford et al. 1991; Pendleton et al. 1994). It is attributed to C-H stretching vibrations of aliphatic hydrocarbons contained in the carbonaceous component of the diffuse ISM dust. Sandford et al. (1995) decomposed the observed 3.4 μm profiles into contributions due to methyl (-CH_3) and methylene (-CH_2-) groups and derived an average -CH_2-/-CH_3 ratio of 2.5 ± 0.4 for the interstellar hydrocarbons and densities of this carbonaceous material in the GC and the local ISM. In Fig. 6, the observed profiles are compared with meteoritic and laboratory analogue measurements. The comparison reveals a striking similarity of the interstellar profile with that of the carbonaceous component of the Murchison meteorite.

The strong silicate bands at 9.7 and 18.7 μm observed in some GC sources (cf. Roche 1988; Aitken 1989) and in some heavily obscured supergiants and other intrinsically bright stars are also interpreted as being due to absorption by diffuse ISM clouds of the foreground. Concerning the GC sources, it cannot be excluded that the bands also contain silicate absorption of molecular cloud dust. Both the strength of the Si-O stretching bands of the interstellar silicates and the C-H stretching bands of the interstellar hydrocarbons correlate with the visual extinction, a characteristic that would be expected if both band cariers reside in the diffuse ISM. The relationship is, however, not a strictly linear one (see Fig. 7) but is of the same type for both dust components. This could suggest a coupling of both components (grain models with silicate cores and carbonaceous mantles, inhomogeneous grains, cf. Table 4). On the other hand, the nonlinear increase indicates that the grains responsible for the main part of the visual extinction are not identical with those responsible for the bands.

3.2.2 Scattering, luminescence, and thermal emission

Bright stars illuminating nearby dust clouds produce reflection nebulae by light scattering. Scattered starlight of all stars located near the galactic plane is the main contributor to the diffuse galactic light background from UV to NIR wavelengths. Sometimes dark clouds, e.g., globules, show bright rims due to scattering of the interstellar radiation field by the dust grains in the outskirts of the cloud. From the scattered starlight the wavelength dependence of the grain albedo $\gamma(\lambda)$ and the asymmetry factor g can be derived. These quantities are defined by

$$\gamma(\lambda) = \frac{Q_{\rm sca}(\lambda)}{Q_{\rm ext}(\lambda)} \qquad \text{and} \qquad g = \langle \cos(\alpha) \rangle, \tag{3}$$

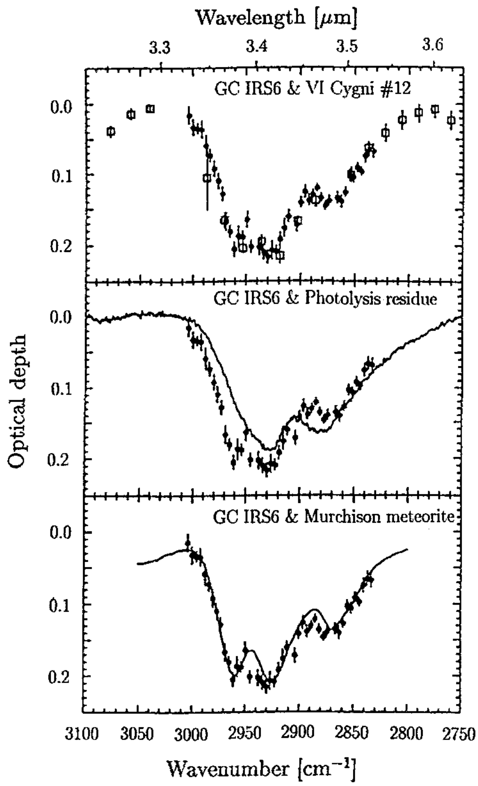

Fig. 6. Comparison of the 3.4-3.5 μm profiles of the sources GC IRS 6E (*filled circles*) and Cyg OB 2 # 12 (*open squares*, upper graph) with a laboratory residue produced by UV photolysis of an interstellar ice analogue (middle graph) and with the carbonaceous phase of the Murchison meteorite (lower graph). After Sandford et al. (1995)

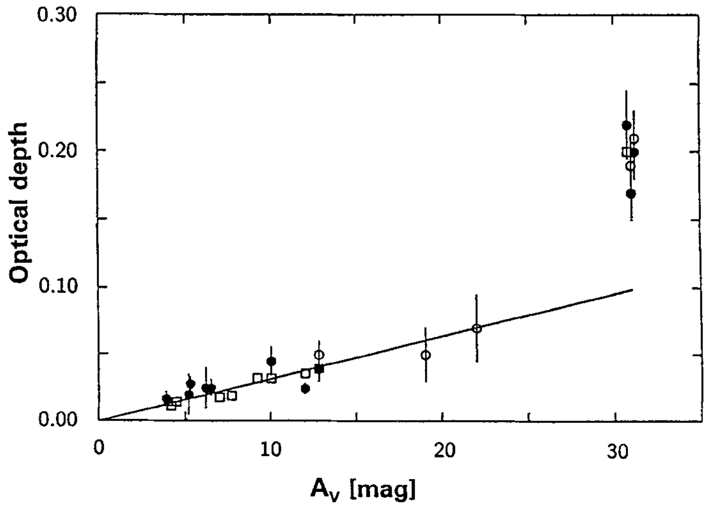

Fig. 7. Optical depths τ of the 9.8-μm silicate band (*open squares*, values scaled by a factor 1/18 to normalize them to the strength of the 3.4-μm band at the Galactic Centre) and the 3.4-μm hydrocarbon band (*filled circles* low-resolution data; *open circles* high-resolution data) vs the visual extinction A_V. After Sandford et al. (1995)

wherein Q_{sca} and Q_{ext} are the efficiencies for scattering and extinction, respectively and $\langle\cos(\alpha)\rangle$ is the weighted mean of the cosine of the scattering angle α with the scattering function $\varphi(\alpha)$ as the weighting function.

Results of the determination of these dust parameters have been reviewed by Witt (1989). Representative values for the visual wavelength range are $\gamma = 0.6 \pm 0.1$ and $g = 0.6 \pm 0.2$ (isotropic scattering: $g = 0$; total forward-scattering: $g = 1$). This points to dielectric grains with sizes comparable to those of the big grain mode in the extinction models (grains with sizes of the order 0.1 μm). However, the dust properties derived from scattered light are affected by greater uncertainties than those derived from extinction observations. Surface brightness levels comparable to the night sky brightness are much more difficult to measure than stars. Mostly, the analysis includes a radiation transfer problem, and in the case of reflection nebulae assumptions on the geometric arrangment of dust cloud and illuminating stars are necessary. The diffuse light analysis provides galactic averages of dust properties, whereas the properties derived from reflection nebulae concern individual clouds.

As an additional information source on ISM dust, measurements of scattered light in the UV and FUV have become of growing importance. Early data on the diffuse galactic light measured by the OAO-2 satellite showed that the dust albedo is strongly reduced within the range of the 217.5-nm extinction feature (see Witt 1989). This effect clearly underlines the pure absorption nature of this band. New observations of the best-studied reflection nebula, NGC 7023, with the Ultraviolet Imaging Telescope of the Astro-1 mission (Witt et al. 1992) confirmed this finding. The albedo in the range of the 217.5-nm feature was indeed reduced by about 25 to 30%. This value is compatible with the strength of this feature in the extinction curve of the illuminating star HD 200775. Somewhat contradicting this result is the earlier detection of enhanced scattering in the red wing of the 217.5-nm band in the reflection nebulae IC 435 and Ced 201 (Witt et al. 1986, 1987). However, these results need confirmation. The data on NGC 7023 also showed that the scattering functions of the grains in the near and the far UV (up to 140 nm) must be strongly forward directed ($g \approx 0.75$) with an albedo of $\gamma \approx 0.65$ (Witt et al. 1992). From the same reflection nebula, for the first time sub-Lyα albedo values have been derived. Murthy et al. (1993) found $\gamma = 0.5$ at 110 nm which is considerably smaller than the value $\gamma = 0.7$ measured at 180 nm. From their analysis of the diffuse galactic background in the range 141.5-183.5 nm, Hurwitz et al. (1991) found some indications for low albedo values (0.13-0.25) and isotropic scattering, which contradict the values derived from reflection nebulae.

The IR spectra of reflection nebulae show a surprisingly strong emission in the range from 2 to about 13 μm, which is far in excess over the expected level of scattered light and also over that of the thermal emission from dust in equilibrium with the radiation field of the illuminating star. This MIR continuum is characterized by a colour temperature of about 1000 K which is the same in most nebulae, independent of the distance from the star (for a review see Sellgren 1989). The mechanism proposed by Sellgren et al. (1983) and in more detail by Sellgren (1984) explains this excess as being due to non-equilibrium thermal emission of nanometre-sized grains which are stochastically heated to high temperatures by the absorption of single stellar UV photons. Alternatively, the excess radiation may be explained in the frame of the PAH hypothesis (Léger and Puget 1984) which we already mentioned in connection with carbonaceous stardust. In the latter case, the emission is assumed to be fluorescence radiation of large PAH molecules excited by UV radiation.

Closely connected with the explanation of the continuous IR spectrum of reflection nebulae is the explanation of discrete spectral features observed in these objects. Sellgren et al. (1985) detected the main unidentified IR emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm in the reflection nebulae NGC 7023 and 2023. Since that time, reflection nebulae form an important subgroup of the wide range of sources showing the UIB emission (cf. Sect. 2). The association of these five emission bands with the MIR continuous emission lent support to the idea that these bands were also due to very small grains and/or PAH molecules. The connection between small grains, PAH molecules and the infrared cirrus and the effort to identify the bands by studying laboratory analogues have recently been reviewed by Sellgren (1994). Meanwhile the emission features at 3.3 (Giard et al. 1994a and references therein) and 6.2 μm (Ristorcelli et al. 1994) have been detected as a large-scale diffuse emission in the Galaxy.

Apart from the UIBs, in reflection nebulae a broad band (FWHM 60-100 nm) in the red and NIR peaking at about 700 nm was detected (for review see Witt 1989). This "extended red emission" (for short ERE) was explained as a luminescence band due to hydrogenated amorphous carbon (Duley 1985; Witt and Schild 1988; Witt and Boroson 1990). The likely excitation source for the ERE are mid-UV photons from the illuminating star. As the UIBs the ERE has also been detected in planetary nebulae (Furton and Witt 1992). Duley (1988) pointed to sharp emission lines in the ERE of the Red Rectangle and compared them with the zero-phonon lines accompanying the broad band photoluminescence of diamond. Several of these emission lines that appear at wavelengths not far from the positions of certain DIBs point to a close connection with this phenomenon (for details see Herbig 1995).

Apart from the diffuse galactic light due to the scattering of starlight by the dust grains near the galactic plane, the interaction between dust and the interstellar radiation field produces a second diffuse galactic emission in the IR. It is due to the portion of starlight absorbed in the grains that is transferred to thermal energy and reradiated by the grains in the FIR. The full extent of this thermal radiation output of the Galaxy became visible only after the IRAS observations (Low et al. 1984; Cox and Mezger 1989; Sodroski et al. 1989). Meanwhile, new FIR results have been obtained by the Far-infrared Absolute Spectrophotometer (FIRAS) and the Diffuse IR Background Experiment (DIRBE) of the COBE satellite (Wright et al. 1991; Sodroski et al. 1994).

IRAS opened a new era of global ISM studies by the discovery of the cirrus clouds in the passbands at 60 and 100 μm. Surprisingly, this filamentarily distributed emission turned out to be a widespread component of interstellar matter accounting for a dominant fraction of the diffuse IR emission of the Galaxy. The 100 μm intensity of the cirrus showed correlations with many interstellar gas and dust parameters and, thus, became a very important means to study the diffuse ISM (see Cutri and Latter 1994). From the IRAS 60- and 100-μm fluxes global galactic dust temperatures and gas-to-dust ratios for H I-, H II-, and H_2-dominated phases of the ISM were derived (Sodroski et al. 1989).

Whilst the FIR cirrus emission can be explained by dust grains in thermal equilibrium with the interstellar radiation field, Boulanger et al. (1985) also found cirrus emission in the MIR IRAS passbands at 12 and 25 μm, which was far in excess of equilibrium emission of dust. These observations underlined the occurrence of very small grains ("nanograins") which are stochastically heated to temperatures of some hundred K by the absorption of single stellar UV photons as a phenomenon not only confined to regions with enhanced UV radiation, e.g., reflection nebulae and

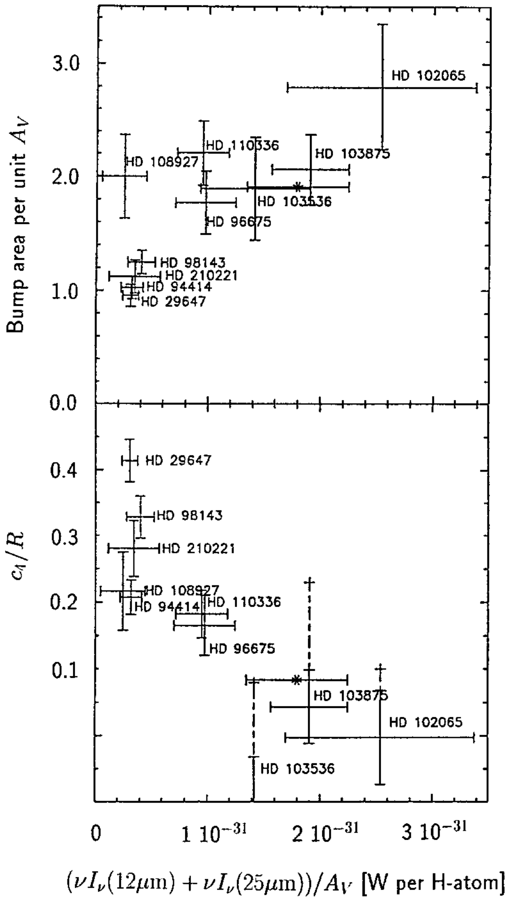

Fig. 8. Correlations between mid-IR emission data and FUV extinction parameters. *Upper graph*: 217.5 nm bump area per A_V vs normalized flux in the 12 and 25 μm IRAS passbands. *Lower graph*: analogous plot for c_4/A_V. c_4 is the non-linear FUV rise coefficient in the parameterized representation of the extinction curve by Fitzpatrick and Massa 1990. After Boulanger et al. (1994)

H II regions, but occuring on the whole diffuse ISM scale including intermediate and high galactic latitudes. Already the former discussion of the FUV extinction curve had underlined the need for postulating nanograins. Boulanger et al. (1994) found connections between the particles responsible for the mid-IR emission and those responsible for the 217.5-nm feature and the FUV extinction. The intensity of the 12- and 25-μm emission turned out to be weakly correlated with the 217.5-nm bump area and more strongly with the non-linear far-UV rise (see Fig. 8).

The COBE FIRAS and DIRBE measurements confirmed the IRAS dust results in the FIR on the whole (Wright et al. 1991; Sodroski et al. 1994; see Fig. 9). From the FIRAS results which show the FIR emission peak at about 140 μm, Draine (1994) estimated T=18$\pm$2K as a "typical" temperature of dust grains in the diffuse clouds of the solar neighbourhood. From the DIRBE results at the wavelength bands 140 and 240 μm, Sodroski et al. (1994) concluded that 60-75% of the FIR luminosity arises from cold dust (17-22K) associated with diffuse H I clouds, 15-30% from cold

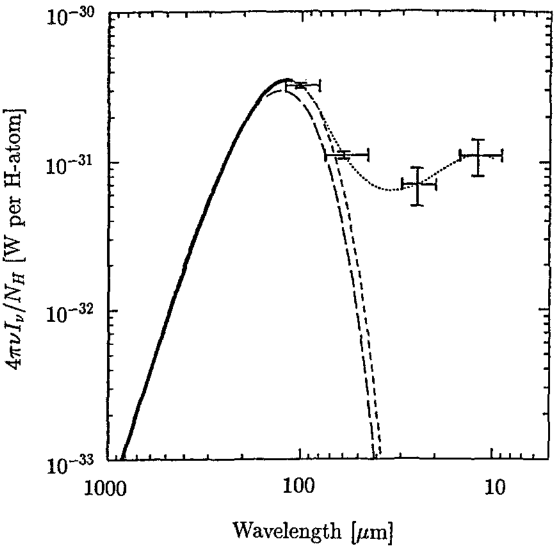

Fig. 9. IR emission spectrum of the interstellar dust after COBE FIRAS data (Wright et al. 1991) compared with the IRAS 100, 60, 25, and 12 μm emission per hydrogen atom (Boulanger and Pérault 1988). The COBE data (*solid line*) were normalized to join to the IRAS 100 μm flux. The *dashed lines* are two extrapolations to shorter wavelengths. For details see Draine (1994)

($\approx$19K) dust associated with molecular gas and less than 10% from warm ($\approx$29K) dust in extended low-density H II regions, consistent with the IRAS results.

3.2.3 Interstellar polarization

Apart from extinction and reddening dust grains are responsible for the linear dichroism of the ISM. This effect can be explained by elongated dust grains which are aligned by interstellar magnetic fields. The discussion of the alignment mechanism is out of the scope of this review (see, e.g., Whittet 1992). The degree of the resulting linear polarization is wavelength-dependent. The polarization curve $P(\lambda)$ has a broad maximum in the visual with its peak at $\lambda_{\max}$ varying from 350 to 900 nm; its typical value is 550 nm. A well-studied parameterized representation of the polarization curve (see Whittet 1992 and literature therein) is

$$\frac{P(\lambda)}{P_{\max}} = \exp[-K \ln^2(\frac{\lambda_{\max}}{\lambda})] \quad (4)$$

In contrast to the expectations of Serkowski (1973) who originally found this expression, K turned out to be a linear function of $\lambda_{\max}$. Whittet et al. (1992) derived the relation $K = (0.01 \pm 0.05) + (1.66 \pm 0.09)\lambda_{\max}$. The decisive parameter $\lambda_{\max}$ is tightly correlated with the extinction parameter R (see, e.g., Martin 1989; Whittet et al. 1992). This points to the fact that aligned and nonaligned components of the interstellar dust population are influenced in the same way by environmental changes.

Up to now, only few stars could be studied spectropolarimetrically in the UV. Clayton et al. (1992) succeeded in detecting significant interstellar polarization along six lines of sight with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) during the Astro-1 mission. The wavelength dependence measured on three of these stars was in agreement with the extrapolation of Serkowski's law into the UV, whereas two stars showed excess polarization. The polarization curve of the star HD 197770 showed a surprisingly well-defined bump exactly at the 217.5-nm band position and was in agreement with Serkowski's extrapolated relation below 180 nm. Wolff et al. (1993) discussed additional WUPPE results and found that the bare silicate model by Mathis et al. (1977) (aligned infinite cylinders) gives the best representation of the observed UV wavelength dependence, whereas small aligned graphite disks can explain the 217.5 nm polarization bump of HD 197770. Polarimetry results obtained by the Faint Object Spectrograph of the HST (Clayton et al. 1995) enlarged the number of lines of sight with a positive detection of interstellar UV polarization. Stars with $\lambda_{max} \geq 0.54\ \mu m$ follow Serkowski's law, whereas such with $\lambda_{max} \leq 0.53\ \mu m$ show excess polarization. Even if the number of UV polarization observations is very small, the results suggest the possibility to get a parameterized representation (λ_{max} being the parameter) of the mean interstellar polarization curve over the same wavelength range as the representation of the extinction curve by Cardelli et al. (1989) is valid.

3.2.4 Grain models of the diffuse ISM dust

Mainly from the discussion of the above observational data and to a much lesser extend from theoretical studies of dust destruction, growth and modification of dust grains in the diffuse ISM, for which indirect indications exist, dust models have been proposed that give more or less satisfactory representations of the observed continuous spectral effects (interstellar extinction, diffuse galactic light, FIR emission, polarization etc.) as well as of the profiles of diagnostic or supposedly diagnostic spectral features (silicate bands, hydrocarbon bands, special assumptions on the identity of the 217.5-nm band, of the UIBs etc.).

Typical steps in constructing a dust model are:

- Assume (or attempt to calculate ab initio) chemical composition, shape, and size of each grain type.
- Use measured dielectric properties based on laboratory measurements and/or astronomical observations.
- Calculate the optical properties (absorption and scattering efficiencies) for each grain type.
- Construct appropriate mean values and work with the model.

As the reliably identified spectral features demonstrate, the dust population of the diffuse clouds contains several well-distinguished chemical components. Concerning the chemical components, the current grain models of the diffuse ISM are based on mixtures of refractory grains (volatiles are not stable in the harsh environment of the diffuse clouds and can be excluded!). Favourites are homogeneous carbonaceous grains (graphite, HAC, PAHs) and oxidic grains (amorphous (Mg-dominated) silicates, Mg-Fe oxides) and/or inhomogeneously composed grains.

Apart from these main chemical components some minor ingredients can be expected, e.g., sulfide grains (Begemann et al. 1994). On the other hand, there are problems to understand the absence of silicon carbide among the main components. As has been discussed in Sect. 2, carbon-dominated AGB stars should produce SiC grains with an abundance of the same order of magnitude as the silicate grains. However, interstellar 11.3 μm absorption has not been found. In a sense, this result is confirmed by the extreme low abundance of the presolar SiC grains in meteorites. On the other hand, these meteoritic grains prove that some SiC is present in the diffuse ISM. The relatively large sizes of these grains suggest that the smaller ones have been effectively destroyed or removed otherwise by an unknown mechanism. Attempts to explain this enigmatic behaviour of SiC (Whittet et al. 1990; Kosaza et al. 1995) did not present the ultimate solution of the problem.

The materials of the inhomogeneous particles can be considered as effective media consisting of silicates, carbonaceous components, iron and iron oxides and vacuum (porous grains). The optical behaviour can be approximately treated by the mixing rules of the effective-medium theory (see Ossenkopf 1991). The grain models cover a wide range of structure types from the simplest case of spherical or cylindrical core/mantle-grains to coagulated grains built up from regular (spherical) subgrains and finally fractal grains. Exact solutions for the interaction with electromagnetic radiation only exist for simple configurations such as spheres, ellipsoids and infinite cylinders (Bohren and Huffman 1983). The cross-sections of irregularly shaped grain aggregates can be calculated by different methods which are summarized by Stognienko et al. (1995).

Apart from the optical constants, the size of a grain is an important parameter for the calculation of the cross-section of a dust grain. Therefore, a basic function of wide astronomical interest is the radii distribution function $n(a)$ of the interstellar dust grains which cannot be determined in a unique way from observations. Since the contribution of each dust component to the interstellar extinction is proportional to $a^2 Q_{ext}(a, \lambda) \times n(a)$, with Q_{ext} being the extinction efficiency factor, the particle radii distribution can be be determined only by making assumptions on the optical constants of the grain material and the special details of the grain model. The current practice for deriving the grain size distribution is to postulate a mixture of dust components supposed to be ingredients of the diffuse cloud dust, for which optical constants are well-known, and to calculate functions $n(a)$ that fit the observed wavelength dependence of the extinction.

Greenberg (1973) was the first to decompose the extinction curve into characteristic grain size domains and discerned three modes of grains: a big (≈ 0.1 μm) mode of dielectric "classical grains" responsible for the visual and NIR extinction, a small or very small "bump" mode for the 217.5-nm band carrier (graphite grains), and a very small FUV mode reaching the nanometer range (silicates). Concerning the size distribution, especially that of the "classical grains" Greenberg recommended using a radii distribution function of the type (see, e.g., Hong and Greenberg 1978)

$$n(a) \propto \exp(-Ca^3) \tag{5}$$

Such distribution functions are obtained as solutions of the differential equation describing a steady-state between collisional grain destruction and continuous grain growth by condensation of gas. The parameter C depends on the probability per unit time that a particle of the size a is destroyed and on the grain growth rate. Originally this condition was postulated in the classical grain model by Oort and van de Hulst (1946).

More commonly used size distributions for the diffuse ISM dust are smoothed power laws with a sharp upper cut-off at about 0.2 μm. They go back to Mathis et al. (1977, MRN) who had found that

$$n(a) \propto a^{-3.5} \tag{6}$$

Table 4. 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 very small size intervall, exp exponential law (see Equ. 5), g giant grains in the order of magnitude 10 μm, p power law (MRN, see Equ. 6), vs very small grains

Authors (year)	Grain type Composition	Size distr. function	217.5 nm carrier
Draine and Lee (1984)	bare grains SIL, GRA	p	GRA
Chlewicki and 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 and Whiffen (1989)	coagulated + bare grains coagulated: SIL, GRA, HAC, bare: GRA	p	GRA
Wright (1989)	fractal		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 and Krügel (1992)	bare grains SIL, AC, GRA, PAH	p	GRA

gives a satifactory representation of the extinction curve if a varies between the lower and the upper size cut-offs a_-=0.005 μm and a_+=0.25 μm, respectively. They got this result by fitting the mean extinction curve in the wavelength range from 0.11 to 1 μm assuming a model of spherical graphite and silicate grains. Assuming a lower size cut-off is necessary because setting the lower integration limit a_-=0 would prevent the integral expression for the extinction from converging. Considering the very small grains discussed in the recent dust models (cf. Table 4), the value a_-=0.005 μm is certainly somewhat too large. On the other hand, with the exception of the diamonds the presolar grains in meteorites are larger than the upper size limit a_+=0.25 μm.

Power laws of the MRN type are to be expected in the result of fragmentation by grain-grain collisions (see, e.g., Dorschner 1982). Other processes modifying the size distribution of interstellar dust do not necessarily lead to such simple distributions (see Sect. 3.3). Recently, Kim et al. (1994) extracted size distributions from extinction and polarization curves by adopting the MRN model, but using the more sensitive maximum entropy method (MEM). Applying MEM, it is advantageous to have flat curves. Therefore, the authors used a modified mass distribution, $m(a)a$, which is also favourable for the implementation of cosmic abundance and depletion constraints, instead of the number distribution $n(a)$. The resulting distribution deviated

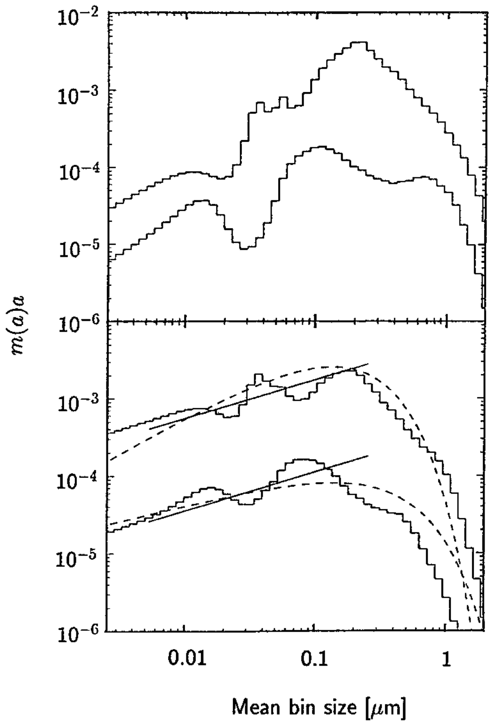

Fig. 10. Mass distribution histograms derived from parameterized extinction curves with R=3.1 (diffuse clouds, *lower graph*) and with R=5.3 (dense clouds, *upper graph*) by applying MEM. The upper histogram in each graph is derived for bare silicate grains and the lower one for bare graphite grains (for clarity scaled down by a factor of 10). The *straight lines* in the lower graph are the MRN power law, the *dashed lines* are power laws with exponential decay. The latter give satisfactory approximations to the histograms. After Kim et al. (1994)

from the MNR power law and showed a much less sharp upper cut-off (Fig. 10). Kim and Martin (1995) extended their analysis also to polarization data using spheroidal particles.

In Table 4, the parameters of some important dust models currently under consideration in the literature have been summarized. Most of them have been developed in order to explain quantitatively the mean extinction curve, prominent IR absorption features, and the galactic FIR emission. Quantitative representations of the observed wavelength dependence of the interstellar polarization imposing stringent conditions on the grain shapes and the representations of UIB profiles were outside the scope of these models. All models in Table 4 include silicates for the explanation of the well-known vibrational bands at 9.7 and 18.7 μm and carbonaceous phases in order to explain the 3.4 μm absorption bands and the extinction bump at 217.5 nm which, with the exceptions of Williams (1989) and Désert et al. (1990), who based their explanation on silicates and "carbon-dominated very small grains", respectively, was explained by small graphite grains. Strong and weak points of the models have been discussed in the review by Draine (1994). Some important problems are: the lack of good optical constants of the individual components over broad wavelength and temperature regions, the poor understanding of the influence of grain shape and porosity, the lack of detailed understanding of the observed polarization and the non-uniqueness of the models (extinction and polarization are integrals over size distribution and optical properties).

3.3 Dust-modifying processes in the diffuse ISM

In the physically harsh environment of the diffuse interstellar clouds, dust grains are expected to undergo a large manifold of processes that destroy or strongly alter them. These factors are very important for the quantitative understanding of grain evolution. They determine the important time scales of this evolution. In the preceding section, some observational indications of such grain changes could be found. They are the cause for the variations of extinction, absorption, polarization, and FIR emission parameters along different lines of sight.

Important physical and chemical factors influencing the grains in the diffuse ISM are (for a review see Draine 1990):

- Grain-grain collisions
- Erosion by sputtering
- Irradiation effects in the grain material
- Grain growth due to recondensation of evaporated or sputtered grain material.

For most of these processes only indirect observational indications exist. They can be investigated only by laboratory simulation or microgravity experiments. Up to now, the efficiencies or yields of these processes are poorly known or a matter of controversy. Extended laboratory work is urgently needed in order to get realistic material data for the astrophysical modelling of grain evolution. In what follows, we restrict our discussion to those processes which play the central role in the current models of dust destruction, modification of solid-state structure and growth in the diffuse ISM.

3.3.1 Grain destruction

The key process for the destruction of diffuse cloud grains is supernova shock waves passing through the warm intercloud medium (WNM+WIM phases of the MO model). In the HIM phase, in spite of its large filling factor the gas density is too low to give a significant grain destruction during the lifetime of a SN remnant, and the small filling factor of the CNM phase excludes a considerable contribution to the overall grain destruction. The modern theory of interstellar shocks with special consideration of the role of and the destructive effects on dust grains has been reviewed by Draine and McKee (1993). Grain destruction rates have been calculated by many authors for different grain models and SN shock wave conditions (for review see Shull and Draine 1987; Seab 1987; McKee 1989; the most recent estimates are by Tielens et al. 1994; Jones et al. 1994).

The destructive mechanisms connected with SN shocks are physical grain erosion by thermal and non-thermal sputtering and grain-grain collisional vaporization. Thermal sputtering means that the removal of surface atoms from the grains is only effected by the gas particles impinging on the grains due to the random thermal motion, whereas in the non-thermal case the sputtering is determined by the velocity of the grains streaming through a "stationary" gas (all incident atoms have nearly the same velocity and direction). High grain-grain collisional velocities leading to annihilation of dust grains by vaporization can be expected in supernova shocks (shocking of the gas, acceleration by turbulence, "betatron" acceleration of charged grains due to magnetic field compression).

For accelerating the grains by the magnetic field, their electric charge is important. Generally, three effects are discussed for charging interstellar dust grains: the photoelectric effect, the thermoionic effect and collisional charging. Within the clouds of the diffuse ISM, the emission of photoelectrons due to absorption of stellar UV photons with energies larger than the photoelectric work functions for the grain material (silicates: 5 eV, graphite: 4.2 eV) is the most important mechanism for grain charging. For the large grains (a near the upper cut-off of the MRN distribution) in standard diffuse cloud conditions (electron density $N_e \approx 0.02$ cm^{-3}, $T \approx 100$ K) and an average interstellar radiation field, grain potential values between 0.1 and 1 V have been estimated (Draine 1978). In contrast to the relativley large positive charge in the neutral gas, the grain immersed in a plasma may aquire a small negative charge (in the order of 10^{-2} V for a grain with $a \approx 0.1$ μm) by collisional charging if the photoelectric emission due to UV photons can be neglected (Draine and Sutin 1987; see also Sect. 4.1.). Very small grains can get much higher charges. The negative sign comes from the fact that per unit of time many more electrons than ions hit the grain surface. The growing Coulomb repulsion between grains and electrons and the increasing attraction of ions that neutralize the negative grain charge keep the grain potential at smaller values than potentials due to the photoelectric effect. The thermoionic effect may become significant only for electrically conducting dust material in such cases where the grain temperature reaches high values (circumstellar environment, temperature spikes by absorption of high-energy photons).

In contrast to sputtering, which steadily removes grain surface atoms and does not reach the grain cores as long as protecting mantles are present, grain-grain collisions can suddenly annihilate grains or, at least, disrupt them, leaving the fragments, including the cores, vulnerable to sputtering.

Apart from physical sputtering, a further sputtering mechanism could operate via chemical reactions ("chemisputtering"). Impinging H and O gas atoms should react with grain surface atoms, especially with carbon atoms, and let them escape as molecules from the grain. The significance of chemical sputtering in the diffuse ISM is, however, controversial (Draine 1990). This process probably only operates in warm regions like protostellar cores (Lenzuni et al. 1995).

Altogether, the efficiency of grain destruction in shocks is still a matter of debate, as is the effective SN explosion rate near the galactic plane. Jones et al. (1994) using algorithms for the destructive processes operating on the grains derived by Tielens et al. (1994) showed that independent of the grain composition the destruction is dominated by non-thermal sputtering for shock velocities in the range from 50 to 150 km s^{-1} and by thermal sputtering in fast non-radiative shocks at higher velocities. It further turned out that the grain-grain collisional process is less important for the grain destruction than previously assumed. For the grain materials discussed for the diffuse ISM, vaporization will occur for collisional velocities in excess of 20 km s^{-1}.

3.3.2 Grain processing

Collisional velocities smaller than those necessary for vaporization shatter the grains and are, thus, a factor strongly modifying the grain size distribution. Additionally, the shock wave propagating through the grain material can alter the solid state by phase transitions. Collisional fragmentation has been studied in great detail with solar system phenomena (asteroids, ring particles; see, e.g., Davis et al. 1989). The main result is that the collisional debris should follow power law size distributions with exponents near 3.5. The significance of the fragmentation process for the interstellar grain size distribution has been pointed out by many authors (Dorschner 1970; Mathis et al. 1977; Biermann and Harwitt 1980; Dorschner 1982; Henning et al. 1989). The success of the MRN size distribution (Mathis et al. 1977) as a kind of standard grain size distribution for the dust in the diffuse ISM, which was confirmed with some modifications by the more accurate modelling of Kim et al. (1994), has underlined the dominating influence of fragmentation for the interstellar grain size distribution.

The possibility of phase transitions was discussed by Tielens et al. (1987). From the low yield of high-density phases measured for shocked silicates, Tielens et al. (1987) conclude that shocked interstellar silicates should show glassy structure due to melting by the shock wave propagating in the grain rather than high-pressure silicate phases. The possible phase transition of carbon was applied to the problem of interstellar diamonds found in primitive meteorites. However, the mechanism thought to transform colliding graphite grains to diamonds has some shortcomings. It is restricted to graphite only, does not include other forms of carbonaceous dust (e.g., the 3.4 μm carrier of the diffuse ISM!), and its yield is very low (5 %). The last point rules out this mechanism for the formation of the meteoritic diamonds. If it had been operating indeed, the meteorites should contain a much larger percentage of graphite with the same isotope signature as the diamonds, which is clearly not the case (Anders and Zinner 1993). Using high-resolution transmission electron microscopy the comparison of the microstructure of the meteoritic diamonds shows more similarities with CVD diamonds than with nano-diamonds produced by shocks in controlled detonations (Daulton et al. 1994).

The favoured mechanism discussed in connection with the meteoritic diamonds seems to be chemical vapour deposition (cf. Sect. 2). However, it is not clear in which environment the diamond formation took place. In contrast to graphite and SiC grains the nanodiamonds are much too small for single grain isotopic analysis. Bulk investigations point to the influence of supernova ejecta (this is especially true for the exotic Xe-HL component which is a unique ingredient of the presolar diamonds, not found in the other presolar phases). However, this does not necessarily mean that diamonds must have been condensed out in this very environment. The carbon isotopes show no significant deviations from the solar system ratio, whereas the nitrogen isotopes are clearly anomalous (Ott 1993a, b). The D/H ratio is comparable with that measured for interstellar molecules and is compatible with the interstellar origin of the bonded H-atoms (Carey et al. 1987; Virag et al. 1989). From their thorough investigation, Huss and Lewis (1994) concluded that the observed isotopic patterns of the noble gases are compatible with the assumption that the diamonds could be an inheritance of the Sun's parent molecular cloud (see also Allamandola et al. 1993). This does not rule out a stardust origin because the grains could have obtained their "interstellar touch" by subsequent modification (impregnation by supernova ejecta isotopes, hydrogenation of the surface atoms etc.).

In the discussion of interstellar processing of dust grains irradiation effects due to UV radiation of the stars, X-rays and cosmic rays play an increasing role. The most important effects are photolysis of grain material, photodesorption by electronic excitation of adsorbed surface atoms or the substrate, dehydrogenation of very small carbonaceous grains, radiation damage and radiation-induced chemical alterations. Refractory organics discussed as a dust components of the diffuse ISM (see, e.g., Greenberg 1989; Désert et al. 1990) are assumed to be formed by photolytic processing of volatile components of molecular cloud dust. Therefore, photolysis is discussed in more detail in Sect. 4.5. High UV flux densities can even dehydrogenate the refractory organic material transforming it to elemental carbon. The role that UV radiation plays in the discussion of processing of carbonaceous interstellar dust is somewhat confusing. Nuth and Allen (1992) proposed that the meteoritic diamonds are formed by annealing of carbonaceous grains produced in a possible carbon-rich supernova precursor or, more likely, already present in the nearby interstellar medium. The intense ultraviolet flux of the supernova breaks all C-H bonds in the carbonaceous grains in the neighbourhood of the supernova, transforming the hydrocarbon material into a carbon phase. The authors suggest that in contrast to larger grains for which graphite is the thermodynamically stable carbon phase, for very small grains diamond may become the more stable phase. Therefore, they propose that as the result of the strong radiation-induced dehydrogenation diamonds are formed. In contrast to other environments with high UV radiation level (planetary nebulae, nova shells), only supernovae are capable of depositing the isotopically distinct Xe-HL marker in the diamonds.

Sorrell (1990) discussed the dehydrogenation and graphitization of HAC by UV radiation and estimated that a sufficient portion of small HAC grains formed in the outflows of carbon stars could be transformed to graphite during their life-time of about 10^8 years (Sect. 3.3.3.). This phase transition should explain the occurrence of the interstellar 217.5 nm feature (see Sect. 2).

Different doses of UV radiation could determine which band in the 3 μm range appears because experiments show that the value of the sp^3/sp^2 ratio is changed by the irradiation (Sorrell 1991; Duley and Williams 1995). Cold HAC mantles around silicate cores (dust model by Williams 1989) in heavily obscured regions should show the 3.4 μm absorption band typical of aliphatic C-H bonds, whereas hot mantles due to UV annealing in clouds with little dust extinction should show the 3.3 μm emission band of aromatic C-H bonds.

The whole complex of grain material processing is a domain of laboratory astrophysics. Up to now, systematic experimental work providing data on dust-relevant materials are lacking. Urgently needed are experimentally determined evaporation rates by shock waves, sputtering yields in the sub-keV range, measurements on chemical sputtering, UV and X-ray irradiation effects, and data on the influence of radiation damage on the optical constants.

3.3.3 Grain growth

Based on the MO model of the diffuse ISM and MRN dust size distributions, Jones et al. (1994) found life-times of 4×10^8 years for carbonaceous and of 2.2×10^8 years for silicate grains. These results are comparable with former estimates (see, e.g., Seab 1987; McKee 1989). Even if there are some effects, e.g., grain porosity and mantling, that prolong this time-scale somewhat, at any rate, the life-time of the grains is too short for the losses by dust destruction to be compensated by stardust injection. The time-scale for replenishing dust in the diffuse ISM by stardust has a typical value of 2.5×10^9 years (see, e.g., Jones and Tielens 1994). In order to maintain the observed interstellar dust density, effective formation of dust in the ISM itself must have taken place.

One dust source compensating the lost refractory solids that returned to the gas phase is the disintegration of molecular clouds by star-formation processes. The disintegration time-scale of molecular clouds is one order of magnitude shorter than that of the dust destruction in the diffuse clouds. One of the disintegration products of molecular cloud dust could be its refractory components mixed among the diffuse clouds. Such "solid fossils" have been found in old star-forming regions, e.g., in the Orion nebula (Sorrell 1992). The transport processes between the different phases of interstellar matter are discussed in Sect. 4.5., where the whole picture of the galactic dust evolution is sketched.

A second important contribution to the interstellar dust could come from the condensation processes within the diffuse clouds. As the observed large elemental depletions of the interstellar gas show, the bulk of the solid material in the grains must be actually condensed out of the interstellar gas rather than in stellar outflows (Draine 1990, 1994). Depletion refers to the underabundance of a gas phase element compared with the standard solar system abundance. The fractional depletion of the element X, $\delta(X)$, is given by

$$\delta(X) = \frac{(\frac{N_X}{N_H})_\odot - \frac{N_X}{N_H}}{(\frac{N_X}{N_H})_\odot} = 1 - 10^{D(X)}, \tag{7}$$

wherein N_X is the number of atoms of the element X, $D(X)$ is the depletion index (logarithm of the ratio of the interstellar to the solar abundance, and $\odot$ labels the solar standard. By spectroscopy of interstellar absorption lines depletion values can be determined with relatively high accuracy.

The depletion index shows some conclusive correlations with other parameters (see Jenkins 1989; Whittet 1992). The higher the condensation temperature of an element the larger is its interstellar depletion. Ca, Al, Ti, Fe, Ni, Cr show fractional depletions $\delta(X) \geq 98\%$, whereas C, N, O, and S have $\delta(X) \leq 50$ %. For refractory elements, the depletion is correlated with the gas density in the clouds. Further, the depletion shows a dependence on the cloud velocity. As a rule, in high-velocity clouds smaller depletion is observed. There is some probability that rapidly moving gas has been recently accelerated by events that vaporized dust grains, e.g., supernova shocks.

Even if there are some puzzles with the depletion (element-to-element variations, the regional variations), there is a consensus among the researchers that the depletion clearly proves that there occurs massive dust formation by condensation processes in the diffuse interstellar clouds. Depletion analyses formed the basis for estimating dust phase abundances of elements (Whittet 1984; Jenkins 1989). Recently, Sofia et al. (1994) derived new depletion data based on measurements of interstellar absorption lines of O, C, N, Mg, Si, Fe, and S with the Goddard High Resolution Spectrograph aboard the Hubble Space Telescope. From these data, fractions of the elements incorporated into core-mantle grains have been derived. More than 70% of the available Fe and Mg atoms is incorporated into grain cores, whereas only 35% of Si is. This points to a core composition which contains not only silicates, but also oxides. Fe and Mg are the main elements in the grain mantles, too. Concerning the mantles, a serious problem with the O atoms arises if the solar oxygen abundance is used as reference. In contrast to the B star reference, with the solar O abundance, half of the O incorporated in the dust must be contained in the grain mantles. It is difficult to understand how to make available such an additional quantity of O. Since the ice absorption band at 3.1 μm is not seen towards the observed stars H_2O offers no solution of the problem. The opposite problem is presented by the dust-phase abundance of C atoms, which is only compatible with the graphite grains necessary for the explanation of the 217.5-nm band if the solar abundance is used as reference and not the B-star abundance.

A serious problem with the common interpretation of the interstellar depletion has been pointed out by Draine (1994). The picture of the frequently occurring change between dust vaporization and recondensation in the diffuse ISM is hardly compatible with dust models (see Table 4) consisting of relatively pure substances (amorphous Mg-Fe silicates, graphitized carbon etc.), even if they are mixed to form agglomerates or core-mantle structures. If most of the material of an interstellar grain is condensed in the cold interstellar space rather than in warm stellar outflows then the seggregation into chemical components could not be easily understood. There is some need to find mechanisms that can accomplish this.

4 Dust in molecular clouds

Within the general uncertainties, there is a rough equipartition between atomic and molecular hydrogen in the disk of the inner Galaxy. Most of the molecular gas component is included in giant molecular clouds with masses between 10^3 and 10^5 $M_\odot$. In addition, there is a huge number of dwarf molecular clouds with masses between 10 and 10^3 $M_\odot$. The nearby clouds are better known under the term dark clouds already indicating the close connection with cosmic dust grains. The grains in these clouds are responsible for the extinction towards the background stars producing striking "holes" in the sky for which the Southern Coalsack is one of the best examples. The presence of solid particles is a necessary condition for the existence of such molecular clouds because in interstellar space an efficient production of molecular hydrogen is possible only on grain surfaces (Hollenbach and Salpeter 1971).

The molecular clouds are highly structured containing filaments and clumps as well as dense and cold cores which are considered to be the birthplaces of stars in our Galaxy. Prior to vigorous star formation, such cores are ideal places for the accretion of molecules onto the grains and the coagulation of these particles. The formation of massive stars in giant molecular clouds leads to a significant heating of their cores (and the grains). In these hot cores, a considerable metamorphism of the dust grains takes place. Especially, the evaporation of grain mantles and the photoprocessing of the accreted material has to be considered. In addition, newly formed stars can drive shocks into the surrounding medium thereby changing the properties of the local dust population by sputtering due to impinging gas particles. The interchange between the molecular cloud phase and the diffuse interstellar medium is an important part of the life cycle of cosmic grains strongly influencing the properties of the dust particles in our Galaxy.

4.1 Dust in cold molecular clouds

Most of our knowledge of the dust properties in cold molecular clouds comes from observations of nearby dark cloud complexes such as the Ophiuchus and the Taurus molecular cloud (TMC) complexes which are the best examples for nearby regions of low-mass star formation. At present, we know of only a few very dense and cold cores without any fully formed stars. Examples are TMC-1 (van Dishoeck et al. 1993), SM 1 in the ρ Oph dark cloud (Ward-Thompson et al. 1989; Mezger et al. 1992), HH24MMS in Orion (Chini et al. 1993), and the globule CB 17 (Launhardt and Henning 1995). It is very difficult to get any direct information on the dust properties in these dense cores because of their high extinction values. Therefore, computational models are an important tool for investigating the possible change of the dust properties. We will discuss such models for the accretion of gas particles and the coagulation of dust grains in the next two sections. Both the depletion of molecules from the gas phase and changed dust opacities are probably involved if we encounter the problem that the gas mass derived from molecular line observations differs from the one derived from millimetre dust continuum observations (assuming that the "interstellar" opacities and dust-to-gas mass ratios are applicable) by at least one order of magnitude (Mauersberger et al. 1992; Krügel and Chini 1994).

In dense molecular clouds, dust grains may carry a substantial fraction of the negative charge. This charge is provided by collisional charging by low-energy electrons because grain-electron collisions are much more frequent than those with the more massive (and slower) ions (Havnes et al. 1987; Draine and Sutin 1987; Umebayashi and Nakano 1990; Nishi et al. 1991). In addition, ions may recombine more rapidly by collisions with negatively charged dust particles than by recombination with free electrons. If the fractional ionization of the gas is very low, grain-neutral collisions can dominate ion-neutral collisions. In this case, the grains become the most important component for the coupling of the magnetic field to the gas. This coupling to the magnetic field by grain-neutral friction has important consequences for the rate of ambipolar diffusion (Nishi et al. 1991; Ciolek and Mouschovias 1994) and the damping of magnetic waves in molecular clouds (Elmegreen and Fiebig 1993).

There is strong observational evidence that dust grains in cold molecular clouds differ from dust in the diffuse interstellar medium. These observations are related to

1. the size distribution of the particles and
2. the existence of molecular ice mantles.

We will first review the evidence for a different size distribution. Cardelli et al. (1989) could show that a parameterization of the interstellar extinction curve over the wavelength interval from 0.1 to 3 μm in terms of a single parameter is possible (see Sect. 3.2.1.). If we use the ratio of total to selective extinction $R = A_V/E(B-V)$, the canonical value for the diffuse interstellar medium is 3.1, whereas we get values up to R=6 for denser cloud regions. In the ρ Ophiuchi dark cloud, a mean value of R=3.99$\pm$0.18 was determined (Vrba et al. 1993). Flatter extinction curves in the UV/visible wavelength range are generally related to a shift of the maximum degree of linear polarization towards longer wavelengths. An empirical relationship of the form R=5.7 ($\lambda_{\max}$/1 μm) was established by Serkowski et al. 1975 (see also, e.g., Vrba et al. 1993) which is in favour of the increase of the mean grain size being the cause for the change of both quantities. There are two processes which increase the mean grain size: accretion of atoms and molecules and coagulation. The accretion process is probably irrelevant for a considerable grain growth. If we assume that all volatile molecules available in the gas phase have been accreted into mantles, the ice mass relative to the mass of the refractory components would only amount to 1.4 (see Ossenkopf 1993). In addition, there is strong evidence that the ratio between visual extinction and hydrogen column density, which has a value of 5.3×10^{-22} mag cm^2 in the diffuse interstellar medium (Bohlin et al. 1978), decreases in dense regions (Jura 1980; de Boer et al. 1986; Cardelli et al. 1989). This can only be explained by the coagulation of particles. A detailed study of the size distribution of dust grains by Kim et al. (1994) comes to the conclusion that the number of intermediate and smaller particles (radius smaller than 0.1 μm) is significantly reduced and that a more modest increase at larger sizes is present (see Fig. 10).

Infrared spectroscopy is the most important observational tool for getting information about the grain mantle composition. There are extended reviews about the observations of molecular ices by Whittet (1993) and especially about carbon monoxide frost by Whittet and Duley (1991). We will not repeat the material presented there, but summarize the main observational results.

There are two classes of objects supplying information about molecular ice mantles by their infrared spectra: background stars behind the molecular clouds and embedded young stellar objects which probe both the circumstellar dust and the foreground molecular dust. Both types of objects show a water ice band at 3.08 μm due to O-H stretching vibrations (see Whittet et al. 1988). There is an extinction threshold for the appearance of this feature which ranges from about 3 mag in the case of the Taurus dark cloud (Whittet et al. 1988; Smith et al. 1993) to about 10-15 mag for the ρ Ophiuchi dark cloud (Tanaka et al. 1990). The threshold is probably related to the desorption by an infrared radiation field (see Sect. 4.6). Superposed on the water ice band is a broad red wing ranging from 3.2 to 3.6 μm, which is typical of molecular cloud dust and is not observed in the spectra of evolved oxygen-rich stars. This wing is very probably caused by C-H stretching vibrations in carbon-rich molecules, although the problem remains that there is no substructure observed near 3.4 μm, which would be expected from hydrocarbons. In addition, Smith et al. (1993) found that the water ice threshold and the red wing threshold are the same in Taurus, which points to the fact that the long-wavelength wing cannot be due to a highly refractory hydrocarbon residue. Examples of such spectra are shown in Fig. 11.

Apart from the 3.08 μm water ice feature the weaker O-H bending vibrations at 6.0 μm are observed. In some sources having very deep 3.08-μm bands, IRAS low-resolution (LRS) spectra have shown the presence of an H_2O band due to libration (hindered rotation) in the wavelength range between 12.5 and 14 μm (Cox 1989).

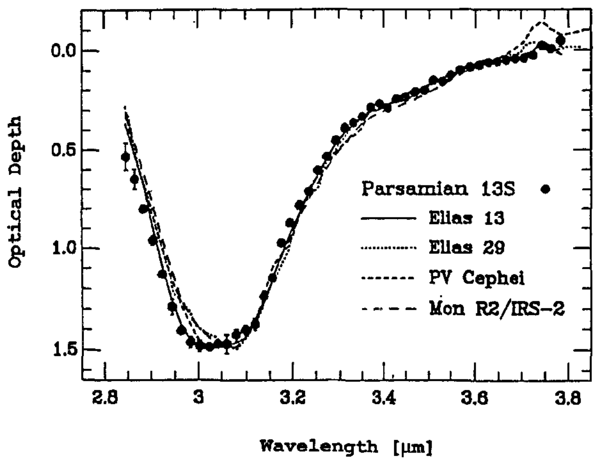

Fig. 11. Water ice band with superposed long-wavelength wing for the cometary nebula Parsamian 13S, Elias 13, representative of dust absorption in the Taurus dark cloud, PV Cep, a pre-main sequence object with a bipolar outflow, the high-mass YSO Mon R2-IRS2, and Elias 29, a PMS object associated with the ρ Ophiuchi dark cloud. All spectra have been scaled so that their maximum optical depth is the same as that of Parsamian 13S. After Smith (1993)

In 1984, Lacy et al. succeeded in detecting solid CO in molecular cloud sources. Meanwhile, a large number of objects was found to show the 4.67 μm feature due to stretching vibrations of solid CO. All sources with the 4.67-μm feature do also show the 3.08-μm H_2O feature, whereas the opposite is not true. This can be easily understood in terms of the different sublimation temperatures for these two types of ices (pure CO: $\approx$20 K, H_2O: $\approx$100 K).

The CO feature consists of two different components which have different strengths in various lines of sight. There is a narrow feature at 4.675 μm and a broader feature centred at 4.681 μm which can be attributed to ice being in a non-polar and a polar matrix, respectively (Tielens et al. 1991; Kerr et al. 1993). We summarize the properties of these features in Table 5 and show typical spectra in Fig. 12. The formation of polar and non-polar ices depends on the H/H_2 abundance ratio. H_2O ice formation dominates in a reducing environment. Because the H/H_2 ratio depends on gas density, the different mantle compositions may reflect different densities in the mantle formation regions. In addition, the temperature can be of importance, especially in the environment of young stellar objects. Non-polar ices sublimate at a lower temperature than polar H_2O ice. In case of the ρ Oph molecular cloud, Kerr et al. (1993) found that the long-wavelength broad feature is prominent in only two lines of sight. The observations indicate that this feature arises in a region close to an embedded object. The short-wavelength feature shows nearly no variation between different lines of sight, indicating that there is little outside influence on the grain mantle chemistry in the denser and well-shielded regions of the cloud. The investigation of the 4.67-μm feature of solid CO in four field stars and two embedded objects in the line of sight to the Taurus molecular cloud shows that the spectra of the field stars are dominated by the narrow (non-polar) ice feature with CO as the main component (Chiar et al. 1995). The embedded objects have broader CO features. In addition, their narrow components show evidence for ice with CO in a mixture dominated by CO_2. This result suggests that CO_2 is being formed by energetic processing of grain mantles due to embedded stars.

Table 5. Components of the CO feature

CO components	Narrow feature	Broad feature
Wavelength centre	4.675 μm	4.681 μm
Wavenumber centre	2139 cm^{-1}	2136 cm^{-1}
FWHM	about 5 cm^{-1}	about 10 cm^{-1}
Matrix material	non-polar matrix (N_2, O_2, CO, CO_2)	polar matrix (H_2O)

It seems to be very interesting to note that there is a correlation between the evidence for thermal annealing from the shape of the ice feature (Smith et al. 1989) and the presence of solid CO. In all cases where evidence for annealing was found, no CO features could be detected (Whittet and Duley 1991).

In contrast to solid CO, the case for solid CO_2 is much less clear. The CO stretching vibrations of this molecule are located at 4.27 μm, a spectral range which is not accessible from the ground because of strong telluric CO_2 absorption. In addition, the wavelength range from 4.1 to 4.5 μm was not covered by the IRAS spectrometer. d'Hendecourt and Jourdain de Muizon (1989) succeeded in the detection of the O-C-O bending vibration at 15.3 μm in the IRAS LRS spectra of a few embedded infrared

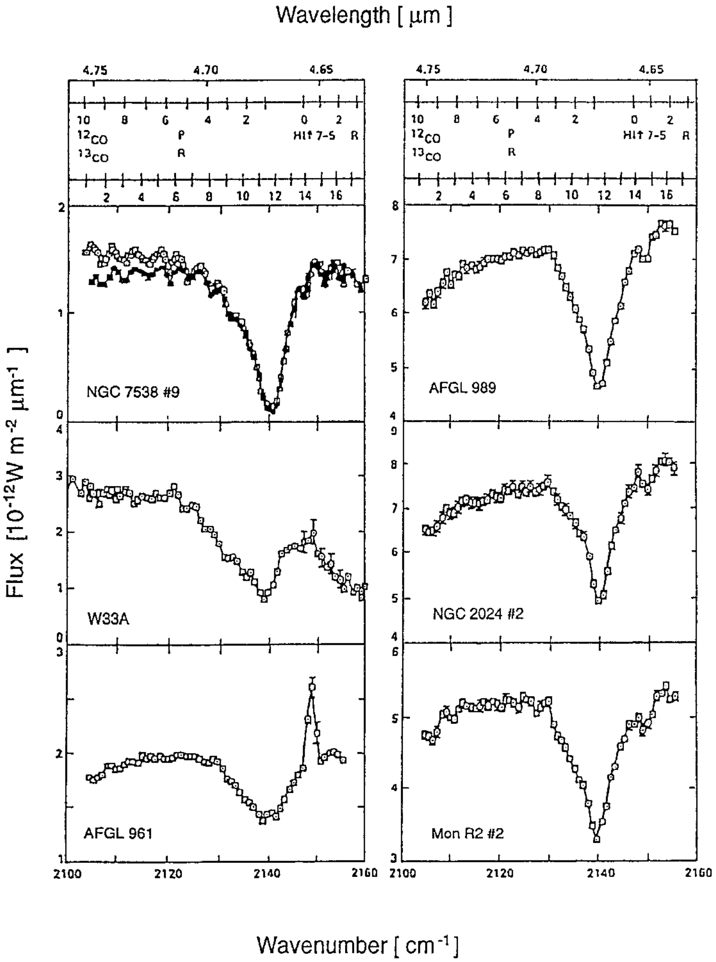

Fig. 12. Spectra with solid CO features. Expected positions of P and R branch ^{12}CO and R branch ^{13}CO lines, and the HI 7-5 recombination line are indicated in the top panel. After Tielens et al. 1991

sources. However, this feature seems not to be very typical of the LRS spectra of YSOs (Whittet and Walker 1991). The ISO satellite is expected to clarify the issue of the abundance of the CO_2 ice.

Apart from the H_2O and CO ice components, the presence of solid CH_3OH in molecular clouds is established by comparing the weak feature at 3.53 μm with laboratory data (Baas et al. 1988; Grim et al. 1991; Allamandola et al. 1992). Figure 13 shows the feature in the spectrum of the massive and strongly embedded YSO W 33A. Solid CH_3OH should have three additional features at 6.85 μm (CH_3 deformation mode), 8.86 μm (CH_3 rock mode), and 9.75 μm (CO stretching vibration). There is a tentative detection of the 8.86 and 9.75 μm features in the spectrum of the young stellar object AFGL 2136 by Skinner et al. (1992). Abundances derived from the observed feature at 6.85 μm contradict the values obtained from the 3.53 μm feature. An obvious interpretation of the data is that CH_3OH is a minor ice component and that the 6.85 μm feature is produced by a superposition of several components. It should be noted that Sandford et al. (1993) detected an additional feature at 2.424 μm in the

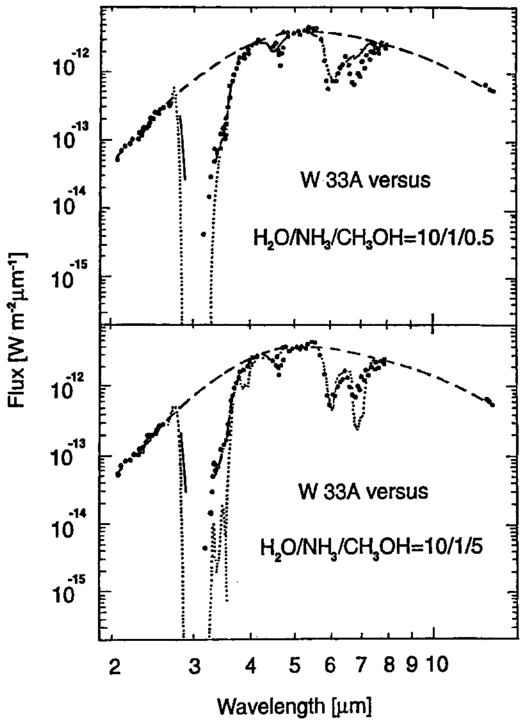

Fig. 13. The weak feature centred at 3.53 μm in the spectrum of W 33A is satisfactorily fitted by the laboratory spectrum of solid methanol. After Baas et al. (1988)

Table 6. Abundance of the main components of ices in molecular clouds

Components	Feature	Mode	N(molecule)/ N(H_2O)	Comments
H_2O ice	3.08 μm	OH stretch	1	
	6.0 μm	HOH bend	1	
	13.3 μm	libration	1	Obvious only in AFGL 961
	45 μm	transverse optical vibration	1	Only in the KL nebula
CO ice	4.67 μm	CO stretch	0-0.50	
CO_2 ice	4.27 μm	CO stretch	-	Not accessible from the ground
	15.2 μm	OCO bend	0-0.20	Only in AFGL 961, AFGL 989, AFGL 890
CH_3OH ice	3.53 μm	CH stretch	0.05-0.10	
	6.85 μm	CH_3 deformation ?	-	Uncertain identification
	8.86 μm	CH_3 rock	-	Only in AFGL 2136
	9.75 μm	CO stretch	-	Only in AFGL 2136

spectrum of WL5, a source deeply embedded in the ρ Ophiuchi dark cloud, which was tentatively attributed to solid CH_3OH. Even more remarkable was the detection of a second feature at 2.415 μm in the spectrum of this source which is probably the first direct evidence for molecular hydrogen frozen in molecular cloud ices.

The evidence for the presence of NH_3 ice and CN-bearing organic molecules is only marginal if it is existent at all. The same statement is also true for sulphur-bearing molecules. For a more detailed discussion, we refer to the paper by Whittet (1993). Table 6 summarizes the abundance of the most relevant ice molecules.

4.2 Accretion of molecules and formation of cosmic ices

In the last section, we reviewed the observational evidence for the accretion of atoms and molecules onto the grain surfaces and the subsequent formation of molecular ice mantles.

Quantum-mechanical calculations of the surface adsorption processes by Leitch-Devlin and Williams (1985) suggest that, at the low temperatures of quiescent molecular cloud cores, the sticking of gas phase species to grains is very efficient. It is a well-established fact that the time-scale for the accretion process in molecular clouds is short or comparable with both the time-scale for ion-molecule chemistry (10^7 year) and the time-scale for the dynamical evolution of the molecular clouds (10^5-10^7 years). This means that the influence of depletion and grain surface reactions has to be considered in molecular cloud studies. The accretion time-scale is given by

$$t_{\rm acc}\ \text{(year)} = 1.5 \times 10^5\ \ (10^4/n)\ \ (1/S)\ \ (2.1 \times 10^{-21}/\sigma_g) \tag{8}$$

where n is the hydrogen number density (cm^{-3}), S the sticking coefficient, and σ_g the mean geometric cross section per hydrogen atom (the value derived from interstellar extinction is 2.1×10^{-21} cm^2). If this time-scale is compared with the free-fall time

$$t_{\rm ff}\text{(year)} = (3\pi/(32G\rho))^{0.5} \tag{9}$$

where G is the gravitational constant and ρ the mass density (see Walmsley 1991), then it turns out that at densities of 10^5 cm^{-3} or higher a considerable depletion of gas phase species during one free-fall time can be expected even if the sticking coefficient is as low as 0.1 (see Fig. 14). Here one should take into account that the free-fall time is a lower limit for the cloud lifetime and that there are no desorption processes considered up to now.

After gas phase atoms and molecules have stuck to the grains, surface reactions can start. Some of the accreted species will be very mobile (e.g., H and O atoms) making possible reactions between them and with other atoms and molecules. Molecular hydrogen must be efficiently produced on grain surfaces because it cannot be formed rapidly enough by a two-body (H+H) reaction in the gas phase. A third body is needed to dissipate the reaction heat. In contrast to heavier molecules, H_2 can evaporate efficiently at the low temperatures of quiescent molecular clouds.

The results of other surface reactions critically depend on the H/H_2 ratio (see, e.g., Tielens and Allamandola 1987). If atomic hydrogen has a fractional abundance in the gas greater than about 10^{-3} (reducing conditions) hydrogenation of O, C, and N atoms will lead to H_2O, CH_4, and NH_3, hydrogenation of CO will produce H_2CO and CH_3OH, and hydrogenation of O_2 produces H_2O_2 and H_2O. At higher hydrogen

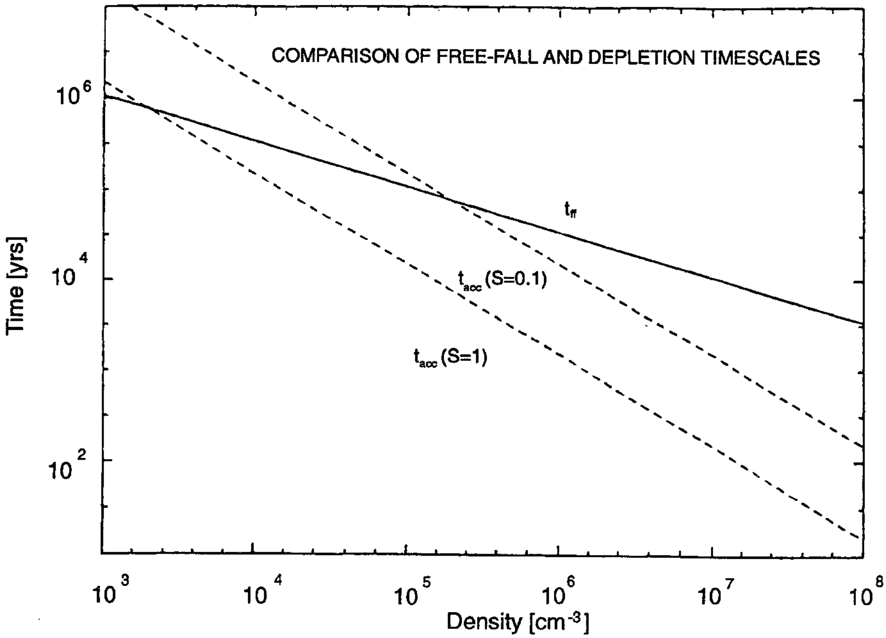

Fig. 14. Time scale for the accretion process as a function of the hydrogen density for two values of the sticking coefficient S. The free-fall time scale is shown for the sake of comparison. After Walmsley (1991)

densities ($\geq 10^4$ cm^{-3}), hydrogen is mainly in its molecular form and inert mantle components such as CO, N_2, and O_2 are expected. If the atomic oxygen abundance is high, CO may be oxidized to CO_2. Surface chemistry may be much less restricted if the proposal by Brown (1990) turns out to be correct. He suggested that the heat release of exothermic chemical reactions can be channeled into translational energy of reaction products leading to the migration of heavier radicals such as CH_3 and OH and opening the possibility for new chemical reactions.

The mantle material should show a large deuterium fractionation which reflects the high gas phase D to H ratio produced by ion-molecule gas phase chemistry. Here we should add that it is very difficult to get any information about the N_2 and O_2 abundance in the grain mantles because these homonuclear molecules are not directly observable.

Time-dependent chemical networks for molecular clouds including surface reactions were calculated by d'Hendecourt et al. (1985), Brown and Charnley (1990), and Hasegawa et al. (1992). A general overview about gas-grain chemistry in quiescent dense molecular clouds was given by Herbst (1993). Hasegawa and Herbst (1993a) considered two-phase grains consisting of a core and a "surface". All condensed phase chemistry takes place on the surface. In a second type of models, Hasegawa and Herbst (1993b) assumed that the dust particles consist of three phases: the core, the mantle, and the surface. The chemical reactions occur in the outermost surface layer. Adsorbed material is chemically inert if once additional material is adsorbed on top of it.

4.3 Coagulation of grains

The coagulation of dust grains in dense and cold molecular cloud cores plays an important role in changing both the size distribution and the internal structure of the particles. The coagulation of grains in dense molecular regions may also influence the properties of the dust population in the diffuse interstellar medium because of an exchange process between these two phases.

Aggregation of dust particles is caused by mutually cohesive collisions. Such collisions cannot only lead to sticking but also to bouncing, shattering, melting, and vaporization of the grains depending on the relative velocities. For compact spherical micron-sized grains, Tielens (1989) found that at high velocities ($v \geq 1$ kms^{-1}), shattering into many small fragments will be important, while at low velocities ($v \leq 10$ ms^{-1}), coagulation will dominate. We should note that there is a very broad gap between these two velocities, which makes possible the distinction between processes leading to coagulation or shattering. Chokshi et al. (1993) derived an expression for the critical velocity for coagulation, i.e. the highest velocity at which sticking will still occur, which is given by:

$$v_{\rm cr} = 4.39 \left(\frac{\gamma^{5/6}\, a_{\rm r}^{2/3}}{E^{1/3}\, m_{\rm r}^{1/2}} \right). \tag{10}$$

Here, γ is the surface energy per unit area, E is Young's modulus of the material, and the quantities $a_{\rm r}$ and $m_{\rm r}$ are the reduced radius and mass of the colliding spherical particles, respectively. Two material parameters are thus important for the coagulation process: the surface energy and Young's modulus. Both quantities determine the area of contact and therefore the binding energy.

Theoretical investigations suggest various processes producing relative velocities between dust grains. In molecular clouds, these processes include thermal, turbulent and gravitational motion, motion caused by incidental particle asymmetries, grain rotation, charges, and the accretion of molecules onto the particles. Ossenkopf (1993) considered all these motions and concluded that the main processes driving the aggregation of dust particles in dense clumps are turbulence at gas densities below 10^8 hydrogen atoms per cm^3 and Brownian motion at higher densities.

The mean relative velocity produced by Brownian motion is given by the expression

$$\langle v_{\rm rel} \rangle = \left(\frac{8\, k\, T\, (m_1 + m_2)}{\pi\, m_1\, m_2} \right)^{0.5}, \tag{11}$$

where T is the kinetic temperature, k the Boltzmann constant, and m_1 and m_2 the masses of the colliding particles. The relative velocity does not depend on the particle structure but decreases with mass. Brownian motion at a temperature of 20 K produces relative velocities which are always less than the critical velocity for sticking. However, the production of large aggregates is not very effective because of the low collisional frequency. The mean relative velocity produced by turbulent motion is

$$\langle v_{\rm rel} \rangle = v_{\rm max}\, (\tau_{\rm f}/\tau_{\rm max})^{0.5}. \tag{12}$$

Here, the quantities $v_{\rm max}$ and $\tau_{\rm max}$ are the turbulence velocity in the largest eddy and its turnover time, respectively. Both are related to each other by the scale length of this eddy $l_{\max}$ by $\tau_{\max}=l_{\max}/v_{\max}$. The quantity τ_{f} is the gas-dust friction time. In addition, one has to take into account the lower cut-off of the turbulence spectrum by the finite molecular gas viscosity (Markiewicz et al. 1991) leading to a lower size limit for the grains which can gain turbulent relative velocities. For this limit, Ossenkopf (1993) estimated a value of 10 nm for a hydrogen density of 10^4 cm^{-3} and 250 nm for densities of 10^9 cm^{-3}.

The structure of grains produced by the coagulation process depends on the size and structure of the colliding particles. Very small grains ($\leq$ 5 nm) have such a high ratio of surface-to-volume energy that they tend to form compact grains in order to minimize their surface area. For larger bodies with sizes above 50 cm and relative velocities of some ms^{-1}, the energy transfer during a collision becomes comparable to the internal binding energy and larger bodies tend to become compact. In the size range between these limiting values, we expect that the shape of the colliding particles will remain the same and that fluffy aggregates will form.

Aggregation of cosmic dust particles can be considered as a ballistic process because the characteristic path length between major changes of the direction of motion of the particles is sufficiently large compared to the grain sizes. There are two limiting cases of the ballistic cluster growth: particle-cluster aggregation (PCA) and cluster-cluster aggregation (CCA). The first process happens if a cluster grows by the addition of single grains, the latter one when the cluster growth is based on the combination of subclusters of identical size. In Fig. 15a and b, we show two clusters each consisting of 1024 single identical grains grown by PCA and CCA, respectively. The sticking factor S was assumed to be 1. Figure 15c shows a PCA aggregate with a power law size distribution of subgrains (exponent -3.15, 2001 subparticles). In Fig. 15d, we display a "core-mantle"-type PCA particle grown by the addition of 2000 identical spherical particles onto a larger core. The PCA particles have a well-defined centre of growth and a relatively spherical shape. CCA clusters show a more filamentary and irregular structure. The optical properties of PCA and CCA particles consisting of astronomically relevant materials were computed by Stognienko et al. (1995).

Which process of cluster growth during the evolution of the grain population will dominate depends on the kind of grains or clusters available during each coagulation step. Ossenkopf (1993) developed a numerical model for the evolution of the dust grain population in dense quiescent molecular cores assuming that these cores are well-shielded from the interstellar UV radiation field and not disturbed by star-forming processes. The simulation explicitly treated the fluffy structure of the aggregates produced in the coagulation process. A dust particle was characterized by its compact volume V (mass over the density of the solid components) and an internal density parameter r defined as $V^{2/3}$ over the average projected area of the particle. Figure 16 shows the evolution of the grain distribution starting with compact grains and a MRN size distribution (Mathis et al. 1977; $f(a) \propto a^{-3.5}$, $a_{\min}$=5 nm and $a_{\max}$=250 nm) taking into account thermal, turbulent, and asymmetry velocities. In Fig. 16d, the evolution of the dust population is modified by the simultaneous ice accretion which produced a mantle of half the volume of the refractory component. Here, we should note, however, that ice accretion is always fast compared to coagulation.

Due to their higher thermal mobility, only the smallest grains coagulate due to Brownian motion (Fig. 16a). Turbulence-induced motion adds a second "hill". It results from the relative velocities of the large grains which are carried through the small eddies sweeping up the small grains which are fully coupled to these eddies.

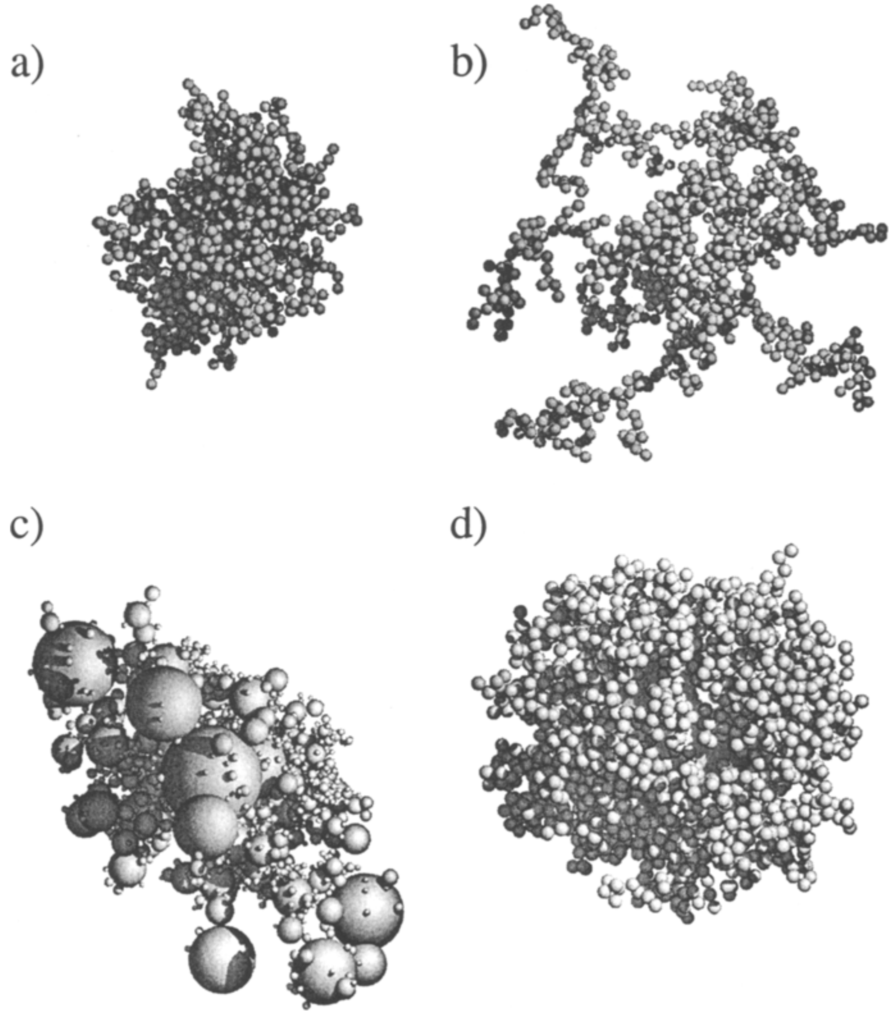

Fig. 15a–d. Examples of aggregates produced by computer simulations: **a** PCA with 1024 monodisperse spherical particles, **b** CCA with 1024 monodisperse spherical particles, **c** PCA with 2001 spherical constituent particles following a power law size distribution with exponent -3.15, **d** PCA with 2000 monodisperse spherical particles aggregated onto a large spherical core. After Blum et al. (1994)

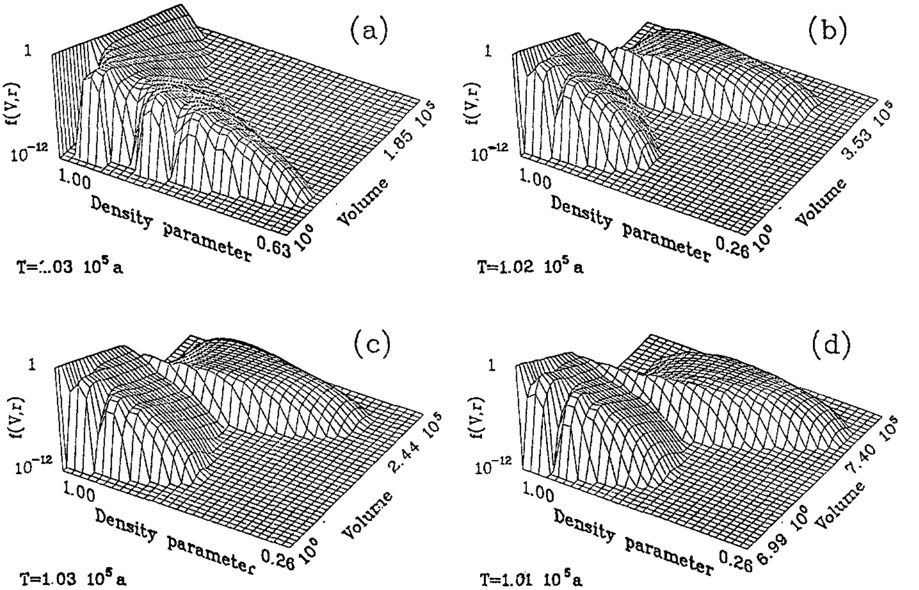

Fig. 16a–d. Dust distribution f (logarithmic scale) as a function of the density parameter r and the volume V (logarithmic scale) after 10^5 years at a density of 10^6 cm^{-3}. **a** Thermal velocities, **b** thermal and turbulent velocities, **c** thermal, turbulent, and asymmetry velocities, and **d** all these motions and the accretion of ice drive the coagulation. Model calculations after Ossenkopf (1993)

Such aggregates consist of a seed of a heavy grain able to decouple from the smallest eddies and of many smaller grains. In Fig. 16c, the "valley" between both regions is partially filled by the additional asymmetry velocities. The additional accretion of ice leads to a shift of the lower size limit of the MRN distribution (see Equ. 6) towards larger values. The shift of the upper limit is smaller due to the lower surface-to-volume ratio of the larger particles. The characteristic features of the coagulation process remain similar. However, the total coagulation rate is increased since the ice mantles simply enlarge the collision cross sections.

Both dust coagulation and ice accretion lead to a rapid growth of the smallest particles whereas the upper grain size limit is only slightly shifted. The distribution becomes narrower on the mass scale and broader on the scale of the internal density parameter.

Starting with a coagulation model, Ossenkopf and Henning (1994) systematically computed and tabulated the opacity of dust in protostellar cores between 1 μm and 1.3 mm wavelength. In comparison to the dust opacity in the diffuse interstellar medium, they found nowhere changes by more than the factor 5 for ice-covered dust grains. For very dense regions ($n_H \geq 10^7$ cm^{-3}), an opacity of 1 cm^{2}g^{-1} at 1.3 mm and for regions of intermediate density ($n_H \approx 10^5$ cm^{-3}), a value of 0.8 cm^{2}g^{-1} is recommended. Krügel and Siebenmorgen (1994) developed a model with fluffy grains composed of subparticles of silicates and amorphous carbon with an admixture of frozen ice. They obtained somewhat higher values for the opacity.

4.4 Dust in hot cores

In contrast to the quiescent cores, the so-called "hot molecular cores" are heated by extremely young OB stars. These stars influence the molecular cores not only by their radiation but also by strong stellar winds and shocks associated with outflows or the expansion of H II regions. The hot cores have diameters of $\approx$0.1 pc, masses of a few solar masses, and temperatures of $\geq$ 100 K. Examples are the Orion Hot Core, the Orion Compact Ridge, G 34.3+0.15, W 51d, Sgr B2(N), and NGC 7538 (Walmsley & Schilke 1993). In the hot core regions, the grain population should be strongly modified especially because the dust temperatures close to newly formed massive stars are sufficiently high to evaporate the grain mantles.

In practice, the hot cores are often "seen" in high excitation ammonia transitions. The derived ammonia column densities in the Orion Hot Core are $\geq 10^{18}$ cm^{-2} over a core region of 0.1 pc. With "normal" [NH_3]/[H_2] abundance ratios between 10^{-8} and 10^{-7}, we obtain unbelievably high molecular hydrogen column densities. Therefore, the general conclusion is that the ammonia must be overabundant. The formation of NH_3 molecules in cold gas phase environments is inefficient due to endothermicities and activation energy barriers of reactions converting N and N^+ into NH_3. Schweitzer (1978) already proposed that the large gas phase NH_3 abundance in hot cores is the result of grain mantle evaporation. In addition, a large degree of deuterium enrichment is observed. Such an enrichment is not explained by gas phase reactions in hot cores because deuterium fractionation is inefficient at the high temperatures. We probably observe the "fossil" signs of cold molecule-ion chemistry frozen in the grain mantles throughout the cloud lifetime, which are evaporated at the high temperatures of the hot cores. Therefore, the investigation of gas phase abundances in hot cores gives us important information on grain mantle composition and grain surface processes.

In the Orion Hot Core, NH_3 and other N-bearing molecules are overabundant, whereas the Orion Compact Ridge, only 5" to the south of the Orion Hot Core, shows an overabundance of CH_3OH and O-bearing molecules. This suggests that grains with NH_3-rich mantles were present in the Orion Hot Core and grains with CH_3OH-rich mantles in the Orion Compact Ridge. The release of simple grain mantle molecules into the gas phase may drive the chemistry in the warm gas, which then leads to molecule formation in situ (Charnley et al. 1992). This opens the possibility of using the molecular abundances as chemical clocks.

Here, one should stress again that not only the heating of dust grains and the subsequent evaporation of mantles may drive the chemistry, but also stellar winds and shocks can be important. In the outflow-envelope interaction regions, an enhanced abundance of the Si-bearing molecules, especially SiO, can be found. This return of Si to the gas phase results from the sputtering and destruction of dust grains in the shocks (see, e.g., Ziurys et al. 1989; Blake et al. 1995). The abundance of sulfur-bearing molecules was also found to be enhanced. This is probably the result of high-temperature reactions.

On the other hand, the possibility of dust nucleation in dense molecular clouds cannot be excluded. We know that quite large carbon chain molecules can form, which may develop into amorphous carbon grains (Thaddeus 1994). In addition, PAHs may form either in the molecular cloud gas phase or in grain mantles (Puget and Léger 1989). Dust condensation in the winds from extremely young stars may be of some importance for interstellar dust although this process is probably not an important source of interstellar dust grains. However, it can produce a chemically distinct dust component.

4.5 Irradiation of ice mantles

Ultraviolet radiation in the less opaque parts of molecular clouds and the immediate environment of very young massive stars as well as cosmic rays can considerably change the structure of the grain mantles (Greenberg 1991). These processes may further alter organic ice mantles during exposure in the diffuse interstellar medium. However, one should note that the flux of low-energy cosmic ray particles irradiating the dust grains is not well-known.

Ultraviolet photolysis of a mixture of water ice and organic compounds leads to the production of a refractory organic residue (Greenberg 1979; d'Hendecourt et al. 1986; Schutte 1988). The UV photolysis of molecular ices produces reactive radicals which can diffuse and react after heating of the mantle to above 30 K, forming more complex organic molecules. Cosmic ray excitation of H_2 molecules results in UV fluorescence and may be an important internal UV radiation source. The cosmic rays can also be important for the transient heating of the grains. Extensive laboratory studies by d'Hendecourt et al. (1986) and Schutte (1988) showed that after the UV exposure of an ice conglomerate and the subsequent heating up, so that the volatile components of the irradiated material evaporate, a small amount of an organic refractory residue remains. In principle, such experiments are modified versions of the famous Urey-Miller experiments. At the higher UV flux densities of the diffuse interstellar medium, there is the possibility that irradiation with UV photons may lead to the formation of amorphous carbon.

Direct observational evidence for the UV photolysis of ices remains scarce. The 4.62 μm feature detected in the spectrum of the deeply embedded source W 33A is generally attributed to a compound produced by the UV photolysis of ice mantles. However, a final assignment of this feature to a specific molecule has not yet been made. Among the proposals are the C≡N stretching mode in nitrile or an iso-nitrile group (d'Hendecourt et al. 1986), the OCN^- ion (Grim and Greenberg 1987), and the SiH stretching vibration in organic-silicon compounds (Nuth and Moore 1988). In addition, this feature is very weak or absent towards other sources and is not of general relevance for the interstellar dust component. However, it was detected in the spectra of some other massive YSOs and T Tauri stars (see, e.g., Tegler et al. 1993, 1995; Weintraub et al. 1994). Palumbo and Strazzula (1993) pointed out that irradiated CO ice produces a broader 4.67 μm feature which provides a better fit to the spectrum of W 33A. Further laboratory experiments for a possible explanation of the long-wavelength shoulder on the 3-μm water ice band by UV irradiated ices are also needed.

Cosmic rays cannot only support UV photolysis but also directly produce both chemical alteration and radiation damage (Pirronello 1993). The first study on the erosion of water ice bombarded by MeV ions was carried out by Brown et al. (1978). Energetic (keV-MeV) ions penetrating into a solid grain deposit energy into the target material by collisions with its atoms and molecules. This can lead to sputtering and to the change of the chemical composition of the target material. The ion bombardment experiments using mixtures of water ice with carbon-bearing molecules show the production of complex organic molecules and can even lead to the formation of a refractory organic residue. The formation process of the residue includes the progressive destruction of C-H or C-O bonds, the loss of the volatiles, and the formation of more stable C-C bonds. An extended ion irradiation finally leads to a complete carbonization of the ice material (Strazzulla and Baratta 1992).

4.6 Desorption mechanisms

In Sect. 4.2., we discussed the short accretion time scales for the gas phase species. To counterbalance the accretion process, a number of desorption mechanisms were proposed. We already mentioned the evaporation of grain mantles in the hot cores and the sputtering by gas particles in shocks. In the following, the different desorption mechanisms will be reviewed. This has to be seen in connection with dynamic transport processes between different regions of a molecular cloud and between molecular clouds and the diffuse interstellar medium.

Thermal evaporation of atoms, molecules, and radicals is only possible at the temperatures of the hot cores. In this case, the H_2O-ice mantle evaporation should be a relatively rapid process. In the regions around luminous young stellar objects, spatially separated regions where the grain mantle composition differs can be expected because of the temperature stratification and the different sublimation temperature of CO, CO_2, and H_2O ice (Tielens et al. 1991).

Desorption by spot heating caused by cosmic ray ions is at best limited to the most volatile species, like CO, unless grain mantle explosions discussed later occurs (Léger et al. 1985). The most effective cosmic ray particles are the Fe nuclei. If the CO is trapped in the H_2O mantle, even the desorption efficiency of CO may be very low. Cosmic rays can also trigger a second process in which H_2 is excited and UV photons are produced by the subsequent decay of electronic states. These UV photons can cause dissociation of molecules and the ejection of surface species (see Hartquist and Williams 1990 for this mechanism and additional references). Willacy and Williams (1993) compared the efficiency of the cosmic ray spot heating and the cosmic ray-induced photodesorption. They conclude that photo-induced desorption is more effective at higher densities. Both mechanisms can have a significant effect on the gas-phase molecular abundances. However, though CO is desorbed in this model it is lost in the gas phase by the production of hydrocarbons and the calculated CO abundance is by at least one order of magnitude too low compared with the observations of the TMC-1 cloud.

An effective chemical desorption not directly depending on the star formation process may happen by explosions generated by stored radicals (see Shalabiea & Greenberg 1994). Possible triggering mechanisms are those induced by energy deposition due to cosmic ray bombardment (Léger et al. 1985) or those induced by grain-grain collisions (Greenberg and Yencha 1973; Greenberg et al. 1983) depending on the density of the cloud. A detailed description of the explosion mechanism was given by Schutte and Greenberg (1991). The Fe collision time scale is about 10^5 year, independent of density. The collision time scale decreases with increasing density and should be shorter than the Fe collision time scale for densities larger than 10^5 cm^{-3}. A problem with this mechanism is whether there is a sufficient production of radicals in the grain mantles accreted in dense cores. Furthermore, the radicals may be reduced by the addition of H atoms in a region rich in atomic hydrogen. In addition, the mechanism does not work for refractory mantle material.

Duley and Williams (1993) proposed that the small energy release associated with the formation of molecular hydrogen on H_2O-ice surfaces inhibits the accumulation of CO in the vicinity of those sites. In this case, freezing-out of CO can occur either on parts of the ice surface that are chemically active, or when the H_2 formation rate is low because the H-atom abundance has been reduced. Willacy et al. (1994) examined the effect of the H_2 formation-driven desorption on the composition of the gas and dust components in a typical quiescent molecular cloud. They concluded that, even if the H_2 formation-driven desorption mechanism has only a moderate efficiency, it dominates the cosmic ray-driven mechanisms discussed at the beginning of this section.

In Sect. 4.1., we mentioned the threshold in visual extinction for the appearance of the water ice feature. Williams et al. (1992) proposed that the onset of ice mantle growth depends on the infrared radiation field. The infrared radiation field at 3 μm removes H_2O molecules weakly bound by physisorption, whereas H_2O molecules in an ice matrix are so strongly bound by H bonds that they are not desorbed. After a monolayer of H_2O has been formed, another deposition mechanism (chemisorption of H_2O molecules) starts. In this case, the mantle can be no longer removed by the infrared radiation field.

Recently, a new desorption mechanism for condensed interstellar CO was proposed by Dzegilenko and Herbst (1995). They proposed that weakly bound CO can be removed from both ice and hydrated silica surfaces by a two-step process in which (a) a neighbouring OH group is vibrationally excited and (b) the energy is transferred to CO by a dipole-dipole interaction.

A strong deficiency of many of the desorption models consists in the fact that the dynamical evolution of the clouds is not incorporated. Boland & de Jong (1982) have proposed that desorption occurs because the clouds are very efficiently mixed by turbulence. Grains from the inner cloud regions can be transported to the surfaces of the clouds where the mantles can be removed by photodesorption. However, both the efficieny of photodesorption and turbulent transport are greatly overestimated in their model. In addition, the clumpy structure of molecular clouds was not taken into account. Goldsmith et al. (1986) suggested that material cycles between high-density clumps and the low-density interclump medium. Clumps are oblated by the stellar winds associated with newly formed pre-main sequence stars. As a consequence, shocks can trigger mantle desorption. On the basis of this scenario, several authors developed cyclic chemical models for molecular clouds with low-mass star formation (see Nejad and Williams 1992 and references therein).

To end this section, we will summarize the grain lifetimes in the different phases of the ISM (see Fig. 17). From a detailed study of grain destruction in shocks, Jones et al. (1994) found lifetimes of $\sim$4x10^8 year for carbonaceous grains and $\sim$2x10^8 year for silicate grains (see also Sect. 3.3.3.). However, we should note that the choice of the individual grain model can have a major effect on the grain destruction results. Jones et al. (1994) found that porosity and mantling may increase the grain lifetime by a factor of $\sim$3. In the three-phase model of the ISM (see Sect. 3.1.1.), destruction of grains in the warm ionized matter will dominate because of its relatively large filling factor. In the hot ionized matter, the densities are too low for significant grain destruction to occur. In addition, this phase contributes only a minor fraction to the total mass of the ISM. The destruction timescales are shorter than the timescale for stardust injection which is estimated to be of the order of 2.5x10^9 year. Therefore, significant grain growth must take place in the ISM. Here, the cold and dense molecular cloud phase is the most important place where such a grain growth by mantle accretion and coagulation can occur. Very large mass exchange rates in and out of the molecular phase are required to fulfil the mass balance in the ISM which implies molecular cloud lifetimes $\leq$2x10^7 year (Draine 1990). The timescale for photoionization of molecular clouds by massive stars is about 10^7 year (Yorke 1986). On a similar timescale, diffuse clouds are converted to warm ionized gas by photoionization. If 10% of the mass of the ISM is in the warm phase, then in a steady state the warm gas is transformed into cold clouds on a timescale of 10^6 years. This is much shorter

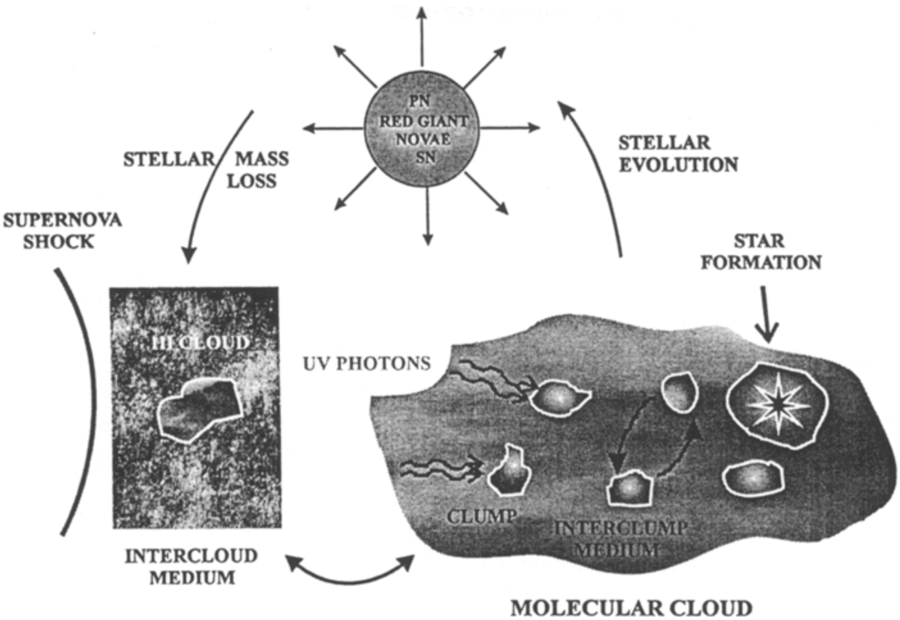

Fig. 17. Transport processes of dust grains. Adapted from Tielens (1989)

than all other relevant timescales. In this respect, the question arises if the dust grains in the intercloud medium are chemically distinct species (formation in the winds of red giants and supernova outflows) or inhomogeneous grains consisting of a mixture of silicatic and carbonaceous material, the basis of the Mathis and Whiffen (1989) grain model (see Table 4). This question is not yet fully answered and depends on the not yet well-determined exchange rates between the different phases of the ISM and the processes leading to the growth of the particles.

Based on the cycling of particles between molecular clouds and the diffuse ISM, Greenberg (1982, 1989) proposed that the grains have mantles of different thickness and composition. The mantles are formed in the molecular clouds and are subsequently photoprocessed in the diffuse ISM. This photoprocessing should lead to refractory organics or in the limit of strong processing to amorphous carbon mantles. This process repeats several times and leads to a multi-layer structure of the mantle. However, it is presently not clear how resistant such a mantle is against shock processing.

5 Environments of very young stellar objects and planetary systems

5.1 Dust around very young stellar objects

In the last two sections, we reviewed the properties of the global dust populations present in the diffuse interstellar medium and the molecular clouds. We will now turn to the more localized dust around young stellar objects. Circumstellar dust emission was detected from all classes of YSOs starting from low-mass stars such as the T Tauri stars and intermediate-mass Herbig Ae/Be stars up to the deeply embedded BN-type objects and the ultracompact H II regions. The thermal continuum emission

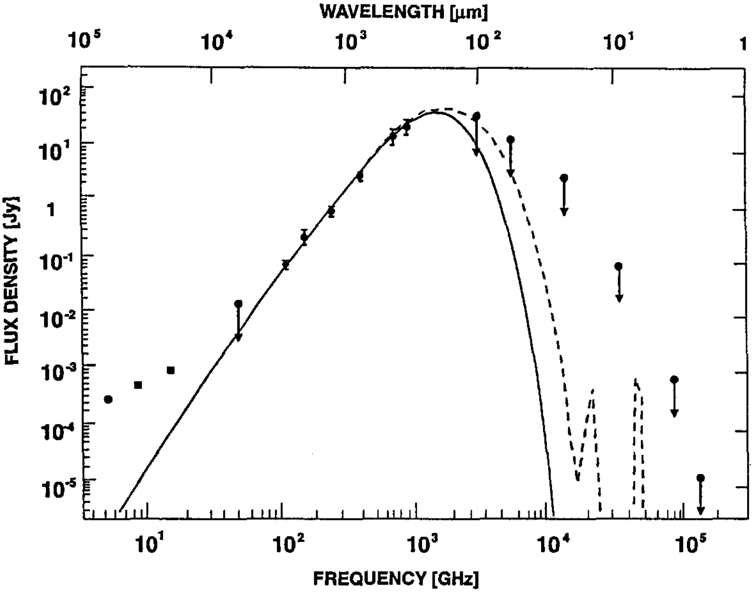

Fig. 18. Spectral energy distribution of VLA 1623 combining data obtained at various telescopes. The *solid curve* is a fit of the form $B_\nu(20\ \mathrm{K})[1\text{-}\exp(-\tau(\nu))]$, where B_ν is the Planck function and $\tau(\nu)$ is the optical depth. The frequency dependence of the optical depth is assumed to be $\nu^{1.5}$. The *dashed curve* is a radiative transfer model. The fluxes at very long wavelengths most likely trace free-free emission from ionized gas. After André et al. 1993

from heated circumstellar grains serves as an important basis for the classification of the objects and is sometimes the only efficient way to detect such sources (see, e.g., Henning 1995). The spectra of objects in very early stages of stellar evolution can resemble single temperature black body curves with temperatures in the range between 15 and 30 K (see Fig. 18). In general, these objects show no emission at wavelengths shorter than 10 μm. The emission comes from configurations which are optically thick below $\approx$100 μm.

Circumstellar disks, spherically-symmetric envelopes, and a combination of both components were used to explain the measured fluxes of more evolved objects. From NIR colour-colour diagrams, Strom et al. (1993a, b) concluded that 30 to 60% of all low-mass stars are surrounded by circumstellar disks. The different arguments for the presence of such dusty disks around T Tauri stars were recently summarized by Beckwith (1994). The search for disk-like structures around luminous YSOs is hampered because these objects are deeply embedded in optically thick envelopes and the observed emission is usually dominated by the dust cocoons (Churchwell 1988; Henning 1990).

Here we should note that the information coming from spectral energy distributions is often not sufficient to constrain the geometry of the dust configuration. In addition, it has been realized that source parameters derived from fitting synthetic dust spectra to the observed energy distributions critically depend on the assumed dust properties (see, e.g., Butner et al. 1990, 1991; Wolfire and Churchwell 1994; Menshchikov and Henning 1995). As an example we mention that small grains which are less efficient emitters at long wavelengths than grains with sizes comparable to these wavelengths are hotter. Therefore, models with smaller grains demand larger envelopes (all other shell and stellar parameters remaining unchanged) to produce the same far-infrared/submillimetre fluxes.

Dust grains around young stars can be modified by UV radiation and heating events. Material falling into the central regions of still accreting stars can be destroyed due to a variety of processes such as direct sublimation, sputtering, and passage of grains through a shock front (Fegley and Prinn 1989; Lenzuni et al. 1995). In protoplanetary disks including the solar nebula, the gases and grains were at least partially reprocessed by thermochemical reactions and shock chemistry (Fegley and Prinn 1989; Prinn 1993). This may explain the wide-spread existence of FeS (troilite) in primitive bodies of the solar system. Another explanation may be that the FeS particles are presolar material (Begemann et al. 1994). During the evolution of protoplanetary disks, dramatic changes of the opacity due to coagulation, collisional destruction, sublimation, and condensation of grains can be expected (see, e.g., Morfill and Völk 1984; Mizuno 1989; Sterzik and Morfill 1994).

We will now concentrate on the following three problems: (i) Is there any spectroscopic evidence for the presence of aromatic hydrocarbons in the circumstellar environment of YSOs? (ii) What is the observational evidence for larger particles? (iii) Is there evidence that the particles are modified by heating processes? For the discussion of infrared spectra of dust-embedded YSOs we refer to the previous section (see also Whittet 1993; Hanner 1995; Henning 1995). The properties of circumstellar dust around YSOs at submillimetre wavelengths were reviewed by Henning (1995).

(i) Small transiently heated dust particles can strongly modify the results of radiative transfer calculations for young stellar objects (see, e.g., Lis and Leung 1991; Siebenmorgen 1993; Natta et al. 1993). In addition, aromatic hydrocarbons (e.g., PAHs) would produce infrared emission bands at 3.3, 6.9., 7.7, 8.6, and 11.3 μm. This family of aromatic emission features is usually seen in regions of high UV flux such as planetary nebulae and H II regions (see Sect. 2.3., Jourdain de Muizon et al. 1990; Zavagno et al. 1992). Therefore, it is perhaps not astonishing that the Orion Trapezium H II region also shows an 11.3 μm feature attributed to aromatic hydrocarbons (Hanner et al. 1995). In contrast to these objects, evidence for the presence of the infrared emission bands in low-mass YSOs and T Tauri stars remains scarce. The 3.3 and 11.3 μm features were observed in the spectrum of WL 16 - a low-luminosity YSO in the ρ Oph cloud (Tanaka et al. 1990; Hanner et al. 1992). A second YSO with a strong aromatic hydrocarbon emission in this cloud is the K0 star Elias 14 (Hanner et al. 1995). Here, the necessary UV flux may be provided by the nearby B2 V star HD 147889. However, the conditions which lead to the presence of infrared emission bands in the spectra of low-mass YSOs remain poorly understood. Even for the more massive Herbig Ae/Be stars, Brooke et al. (1993) showed that only 20% of the objects with observations in the 3.3 μm range have the 3.29 μm feature in their spectra. In addition, a number of ultracompact H II regions showed 11.3 μm emission features in their IRAS spectra (Daines and Kwok 1993). However, it is not clear that the carriers are present behind the ionization shock fronts (see Giard et al. 1994b). Both H^+ chemisputtering or photo-dissociation could destroy PAHs if they are the carriers of the infrared emission bands. The 3.3 μm emission features were also observed in the spectra of IRAS YSO candidates which have IRAS colours typical of reflection nebulae (Suto et al. 1992).

Here it should be noted that in case of aliphatic hydrocarbons dominated by sp^3-bonded carbon, a C-H stretch feature is expected to be located at 3.4-3.5 μm. Such a feature was detected at 3.47-3.48 μm in the spectra of the BN-type objects NGC 7538-IRS9, W 33A, W 3-IRS5, S 140-IRS1, and Mon R2-IRS3 (Allamandola et al.

1992, 1993; Sellgren et al. 1994). However, these spectra are quite different from the 3.4-μm absorption features observed from dust in the diffuse interstellar medium (Sandford et al. 1991, 1993; Pendleton et al. 1994). The spectra of the dust in the diffuse ISM suggest that the material is rich in methyl (-CH_3) and methylene (-CH_2-) groups, whereas the absorption in the molecular cloud/circumstellar dust material may be characteristic of CH stretching vibrations of tertiary C atoms (three of its four single bonds are to other C atoms). However, it is also possible that only a sidegroup is responsible for the molecular cloud dust feature. In any case, the difference between typical spectra again points to the fact that dust in the diffuse medium and in molecular clouds/circumstellar regions around YSOs has a different structure.

(ii) In general, we would expect grain growth in the dense envelopes/disks around YSOs. Several authors (see, e.g., Gorti and Bhatt 1993; Sitko et al. 1994) concluded from an analysis of extinction curves of Herbig Ae/Be stars that the dust is dominated by grains larger in size than the average dust grain in the interstellar medium. However, one should keep in mind that the intrinsic stellar continuum of Herbig Ae/Be stars is often ill-defined which makes the extinction argument for larger grains less striking. In addition, very broad silicate dust features may be caused by an increase in grain size (see, e.g., Hanner et al. 1994). Furthermore, the analysis of polarization maps of YSOs points to the presence of larger particles (Fischer et al. 1995). Another approach is the analysis of flux measurements at submillimetre wavelengths. This is the only efficient way to learn something about the dust population if the objects are deeply dust-embedded. Assuming that the long-wavelength emission can be described by a Rayleigh-Jeans distribution and is optically thin and that the mass absorption coefficient follows a power law $\kappa(\nu)\propto\nu^{\beta}$, the index α of a power law fitted to the observed spectral energy distribution can be directly converted into β by β=α-2. If the emission is optically thick even at the long wavelengths, then the observations give no information about β. Current evidence suggests that the emissivity of particles in disks around T Tauri stars is flatter than for typical interstellar grains (Beckwith and Sargent 1991). This may point to millimetre-sized particles or smaller absorptive grains with a more fluffy structure. However, different factors such as the formation of additional dust components and different temperatures can influence the opacity at long wavelengths (Henning et al. 1995c) and a unique conclusion on the particle size cannot be drawn.

(iii) In the last section, we already summarized some evidence for the UV photolysis and thermal annealing of ices present in the circumstellar environment of YSOs. One could also expect grain annealing of the more refractory dust components in the circumstellar environment of YSOs. Aitken et al. (1988) found an additional narrow feature at 11.2 μm in the silicate polarization band of the luminous YSO AFGL 2591. They interpreted this feature as due to a more structured silicate similar to olivine, which could have been produced in an annealing episode in which grains reach a temperature in excess of 1300 K. However, new measurements by Skinner et al. (1995) show clearly that the AFGL 2591 nebula contains strong hydrocarbon emission, so that the 11.2 μm feature is almost certainly the out-of-plane aromatic C-H bending mode. Spectra of 14 YSOs in the ρ Oph cloud (Hanner et al. 1995) did not give any strong evidence for a "crystalline" 11.2 μm feature. This is also true for the objects S 106-IR and W 51-IRS2 we measured with the spectrometer CGS3 at UKIRT.

5.2 *Vega phenomenon dust*

The detection of dust grains with temperatures of about 100 K around main-sequence stars like α Lyrae (Vega) and β Pictoris by the IRAS mission was a complete surprise (Aumann et al. 1984; Gillett 1986). The thermal emission from the particles totally dominates the stellar radiation for wavelengths larger than 25 μm. This phenomenon is generally described by the term Vega phenomenon, and main-sequence stars with circumstellar dust particles are called Vega-type stars. Most G-type dwarfs (Aumann and Good 1990) and about 20% of late B-, A-, and F-type stars (Patten and Willson 1991) belong to this class of objects. Other lists of Vega-type stars were published by Walker and Wolstencroft (1988) and Backman and Paresce (1993). Here, we do not attempt to give a complete overview of this topic (for this see Norman and Paresce 1989; Backman and Paresce 1993), but we will place the Vega-phenomenon in the general context of dust evolution.

Most of the information about Vega-type stars comes from the prototypes α Lyr, α PsA, and β Pic, which could be spatially resolved by IRAS. An analysis of the data shows that the grains are generally larger than interstellar grains and that the material is probably located in optically and geometrically thin disks with relatively empty inner regions (size of several 10 AU) (Paresce and Artymowicz 1989). The β Pic object has the largest infrared excess among the three prototypes and is the only object with resolved images in the visible and near infrared. Photographic CCD images and $BVRI$ coronographic observations by Smith and Terrile (1984) and Paresce and Burrows (1987) revealed a disk-like structure seen nearly edge-on. In addition, 10-μm imaging shows a thin, marginally resolved disk (Lagage and Pantin 1994). Analysis of the β Pic spectrum (see Artymowicz 1995) indicates that the grain size spectrum peaks around 1 μm. Most of the particles may consist of magnesium-rich silicates producing the emission feature between 9 and 12 μm. If this is true the question arises how dirty ice and carbon-grains are removed from the system. Such particles are expected to be present in protoplanetary systems and in the outer solar system as well. Evidence for the presence of carbonaceous dust was found in a number of Vega-type stars, especially by the detection of infrared emission bands generally related to PAHs (see, e.g., Skinner et al. 1995; Sylvester et al. 1995; Coulson and Walther 1995). The shape of the 10-μm silicate feature detected in β Pic and the Vega-type star 51 Oph agrees quite well with the spectra of the comets P/Halley, Bradfield 1987s, and Levy 1990XX (Knacke et al. 1993; Fajardo-Acosta et al. 1993; Aitken et al. 1993). The 11.2 μm feature observed in the mid-infared spectrum of β Pic was interpreted in terms of crystalline silicates of olivine-type. However, it cannot be excluded that PAHs or related species significantly contribute to this feature.

Artymowicz (1988) showed that particles in the size range between a few times 10^{-2} and 1 μm are rapidly removed from these systems by radiation pressure. Micron-sized grains should be steadily replenished by collisional processes of larger bodies. The current evolutionary picture places β Pic in an intermediate stage between a dusty protoplanetary disk and a solar system-like configuration. However, it is still unknown if the systems already accumulated planetary bodies or will do so at all. Some of the main-sequence stars with infrared excess have ages between 1 to 5 Gyr being old enough to have already formed planetary systems.

6 Future perspectives

We expect strong progress in cosmic dust research over the next years from all three areas: observations, theory, and laboratory astrophysics. Infrared spectroscopy from ground-based telescopes at near-infrared wavelengths and in the 10- and 20-μm range will lead to a better charaterization of dust-related features.

The launch of the Infrared Space Observatory ISO and other air- and space-borne observatories like SOFIA, FIRST, and SIRTF will start a new phase of cosmic dust research. Dust spectroscopy will be definitely extended to external galaxies giving a deeper understanding of these systems. The chemical analysis via impact mass spectrometry (Cassini mission) and the collection of "true" interstellar grains penetrating into the solar system comes within reach. Combined with the analysis of interstellar grains found in primitive meteorites, this will be an especially exciting area of future research.

A deeper understanding of the chemical and structural evolution of grains in the different phases of the interstellar medium is an important goal. Theoretical calculations of these evolutionary aspects taking into account the nucleation of grains from the gas phase, the growth of particles by coagulation and accretion, the destruction of particles by grain-grain collisions, sputtering, and evaporation are strongly needed. The role of very small grains in chemistry and ionization is still an open question. A unified model for interstellar extinction, thermal emission, and polarization must be worked out. In addition, we expect calculations which consider the coupling between hydrodynamics, radiation transfer, chemistry, and dust evolution both for circumstellar envelopes around evolved stars and protostellar/protoplanetary disks.

These calculations need input and support from laboratory experiments. The microphysical radiation-grain, atoms/molecules-grain, and grain-grain interactions need to be explored. Steps in this direction are the measurements of dust opacities over a broad wavelength range and at different temperatures, the study of surface chemistry of cosmic dust analogues, and the investigation of grain-grain collisions by such experiments as CODAG (=Columbus Dust Aggregation). In addition, a breakthrough in the identification of the carriers of the diffuse interstellar bands and the prominent 220-nm band by laboratory studies of carbon-bearing molecules and carbonaceous solids is expected.

References

Adamson A.J., Whittet D.C.B., Duley W.W.: 1990, *MNRAS*, 243, 400

Aitken D.K.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 47

Aitken D.K., Roche P.F., Smith C.H., James S.D., Hough J.H.: 1988, *MNRAS*, 230, 629

Aitken D.K., Moore T.J.T., Roche P.F., Smith C.H., Wright C.M.: 1993, *MNRAS*, 265, L41

Allamandola L.J., Tielens A.G.G.M., Barker J.R.: 1987, in *Interstellar Processes*, D.J. Hollenbach, H.A. Thronson (eds.), D. Reidel, Co., Dordrecht, p. 471

Allamandola L.J., Tielens A.G.G.M. (eds.): 1989, *Interstellar Dust*, Proc. IAU Symp. 135, Kluwer, Dordrecht

Allamandola L.J., Tielens A.G.G.M., Barker J.R.: 1989, *ApJS*, 71, 733

Allamandola L.J., Sandford S.A., Tielens A.G.G.M., Herbst T.M.: 1992, *ApJ*, 399, 134

Allamandola L.J., Sandford S.A., Tielens A.G.G.M., Herbst T.M.: 1993, *Science*, 260, 64

Amari S., Hoppe P., Zinner, E., Lewis R.S., 1992, *ApJ*, 394, L43

Amari S., Zinner E., Lewis R.S.: 1995, in *Nuclei in the Cosmos*. M. Busso, R. Gallino, C. M. Raiteri (eds.), 3rd International Symposium on Nuclear Astrophysics. AIP, New York, p. 559

Anders E., Zinner E.: 1993, *Meteoritics*, 28, 490
André P., Ward-Thompson D., Barsony M., 1993, *ApJ*, 406, 122
Artymowicz P.: 1988, *ApJ*, 335, L79
Artymowicz P.: 1994, in *Circumstellar Dust Disks and Planet Formation*, R. Ferlet, A. Vidal-Madjar (eds.), Editions Frontieres, p. 47
Aumann H.H., Good J.C.: 1990, *ApJ*, 350, 408
Aumann H.H., Gillett F.C., Beichmann C.A., de Jong T., Houck J.R., Low F.J., Neugebauer G., Walker R.G., Wesselius P.R.: 1984, *ApJ*, 278, L23
Baas F., Grim R.J.A., Geballe T.R., Schutte W., Greenberg J.M.: 1988, in *Dust in the Universe*, M.E. Bailey, D.A. Williams (eds.), Cambridge University Press, Cambridge, p. 55
Backman D.E., Paresce F.: 1993, in *Protostars and Planets III*, E.H. Levy, J.I. Lunine, M.S. Matthews (eds.), Univ. Arizona Press, Tucson, p.1253
Baguhl M., Grün E.: 1995, in *Physics and Chemistry of the Interstellar Medium*, C.S. Jeffery (ed.), in preparation
Baron Y., de Muizon M., Papoular R., Pégourie B.: 1987, *A&A*, 186, 271
Beckwith S.V.W.: 1994, in *Theory of Accretion Disks – 2*, W.J. Duschl, J. Frank, F. Meyer, E. Meyer-Hofmeister, W.M. Tscharnuter (eds.), Kluwer, Dordrecht, p. 1
Beckwith S.V.W., Sargent A.I.: 1991, *ApJ*, 381, 250
Bedijn P.J.: 1987, *A&A*, 186, 136
Begemann B., Dorschner J., Henning T., Mutschke H., Thamm E.: 1994, *ApJ*, 423, L71
Begemann B., Henning T., Mutschke H., Dorschner J.: 1995a, *Plan. Space Sci.*, 43, in press
Begemann B., Dorschner J., Henning T., Mutschke H.: 1995b, in preparation
Begemann B., Dorschner J., Henning T., Mutschke H.: 1995c, in preparation
Bernatowicz T.J., Gibbons P.C., Lewis R.S.: 1990, *ApJ*, 359, 246
Bernatowicz T.J., Amari S., Zinner E.K., Lewis R.S.: 1991, *ApJ*, 373, L73
Bertin P., Lallement R., Ferlet R., Vidal-Madjar A.: 1993, *A&A*, 278, 549
Biermann P., Harwitt, M.: 1980, *ApJ*, 241, L105
Blake G.A., Sandell G., van Dishoeck E.F., Groesbeck T.D., Mundy L.G., Aspin C.: 1995, *ApJ*, 441, 689
Blanco A., Bussoletti E., Colangeli L., Fonti S., Stephens J.R.: 1991, *ApJ*, 382, L97
Blanco A., Bussoletti E., Colangeli L., Fonti S., Mennella V., Stephens J.R.: 1993, *ApJ*, 406, 739
Blum J., Henning T., Ossenkopf V., Sablotny R., Stognienko R., Thamm E.: 1994, in *Fractals in the Natural and Applied Sciences*, M.M. Novak (ed.), Elsevier Science B.V. (North-Holland), p. 47
Bode M.F.: 1988, in *Dust in the Universe*, M.E. Bailey, D.A. Williams (eds.), Cambridge Univ. Press, Cambridge, p. 73
Bohlin R.C., Savage B.D., Drake J.F.: 1978, *ApJ*, 224, 132
Bohren C.F., Huffman D.R.: 1983, *Absorption and Scattering of Light by Small Particles*, Wiley, New York
Boland W., de Jong T.: 1982, *ApJ*, 261, 110
Borghesi A., Bussoletti E., Colangeli L., De Blasi C.: 1983, *Infrared Phys.*, 23, 321
Boulanger F., Pérault, M.: 1988, *ApJ*, 330, 964
Boulanger F., Baud B., van Albada G.D.: 1985, *A&A*, 144, L9
Boulanger F., Prevot M.L., Gry C.: 1994, *A&A*, 284, 956
Boutin A., Léger A., Désert F.X., Boissel P., d'Hendecourt L.: 1995, *MNRAS*, 274, 435
Bradley J.P.: 1994, *Science*, 265, 925
Brooke T.Y., Tokunaga A.T., Strom S.E.: 1993, *AJ*, 106, 656
Brown W.L., Lanzerotti L.J., Poate J.M., Augustyniak W.M.: 1978, *Phys. Rev. Lett.*, 40, 1027
Brown P.D.: 1990, *MNRAS*, 243, 65
Brown P.D., Charnley S.P.: 1990, *MNRAS*, 244, 432
Buss Jr. R.H., Cohen M., Tielens A.G.G.M., Werner M.W., Bregman J.D., Witteborn F.C., Rank D., Sandford S.A.: 1990, *ApJ*, 365, L23
Bussoletti E., Colangeli L.: 1990, *La Rivista del Nuovo Cimento*, 13 (12), 1
Butner H.M., Evans N.J., Harvey P.M., Mundy L.G., Natta A., Randich M.S.: 1990, *ApJ*, 364, 164
Butner H.M., Evans N.J., Lester D.F., Levreault R.M., Strom S.E.: 1991, *ApJ*, 376, 636
Cardelli, J.A.: 1994, in *The Infrared Cirrus and Diffuse Interstellar Clouds*, R. Cutri, W.B. Latter (eds.), San Francisco, A.S.P. Conference Series 58, p. 24
Cardelli J.A., Clayton G.C., Mathis J.S.: 1988, *ApJ*, 329, L33
Cardelli J.A., Clayton G.C., Mathis J.S.: 1989, *ApJ*, 345, 245
Carey W., Zinner E., Fraundorf P., Lewis R.S.: 1987, *Meteoritics*, 22, 349
Chan S.J.: 1993, *AJ*, 106, 2126

Chan S.J., Kwok S.: 1991, *ApJ*, 383, 837
Charnley S.B., Tielens A.G.G.M., Millar T.J.: 1992, *ApJ*, 399, L71
Chen P.S., Kwok S.: 1993, *ApJ*, 416, 769
Cherchneff I., Barker, J. R.: 1992, *ApJ*, 394, 703
Chiar J.E., Adamson A.J., Kerr T.H., Whittet D.C.B.: 1995, *ApJ*, submitted
Chini R., Krügel E., Haslam C.G.T. et al.: 1993, *A&A*, 272, L5
Chlewicki G., Laureijs R.J.: 1988, *A&A*, 207, L11
Chokshi A., Tielens A.G.G.M., Hollenbach D., 1993, *ApJ*, 407, 806
Churchwell E.: 1988, in *Galactic and Extragalactic Star Formation*, R.E. Pudritz, M. Fich (eds.), Kluwer, Dordrecht, p. 275
Ciolek G.E., Mouschovias T.Ch.: 1994, *ApJ*, 425, 142
Clayton D.D.: 1992, *Meteoritics*, 27, 5
Clayton G.C., Anderson C.M., Magalhães A.M., Code A.D., Nordsieck K.H., Meade M.R., Wolff M.J., Babler B., Bjorkman K.S., Schulte-Ladbeck R.E., Taylor M.J., Whitney B.A.: 1992, *ApJ*, 385, L53
Clayton G.C., Wolff M.J., Allen R.G., Lupie O.L.: 1995, *Bull. Amer. Astron. Soc.*, 26, 1391
Cohen M., Tielens A.G.G.M., Bregman J.D.: 1989, *ApJ*, 344, L13
Coulson J.M., Walther D.M.: 1995, *MNRAS*, 274, 977
Cox P.: 1989, *A&A*, 225, L1
Cox P.: 1993, in *Astronomical Infrared Spectroscopy: Future Observational Directions*, S. Kwok (ed.), San Francisco, A.S.P. Conference Series 41, p. 163
Cox P., Mezger P.G.: 1989, A&AR, 1, 49
Crutcher R.M.: 1982, *ApJ*, 254, 82
Cutri R.M., Latter W.B. (eds.): 1994, *The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds*, San Francisco, A.S.P. Conference Series 58
Daines J., Kwok S.: 1993, in *Astronomical Infrared Spectroscopy*, S. Kwok (ed.), San Francisco, A.S.P. Conference Series 41, p. 213
Daulton T.L., Eisenhour D.D., Buseck P.R., Lewis R.S., Bernatowicz T.J.: 1994, *Lunar Planet. Sci.*, 25, 313
Davis D.R., Weidenschilling S.J., Farinella P., Paolicchi P., Binzel R.P.: 1989, in *Asteroids II*, R.P. Binzel, T. Gehrels, M.S. Matthews (eds.), Univ. Arizona Press, Tucson, p. 805
de Boer K.S., Lenhart H., van der Hucht K.A. et al.: 1986, *A&A*, 157, 119
de Heer W.A., Ugarte D.: 1993, *Chem. Phys. Lett.*, 207, 480
Désert F.-X., Boulanger F., Puget J.L.: 1990, *A&A*, 237, 215
d'Hendecourt L.B., Allamandola L.J., Greenberg J.M.: 1985, *A&A*, 152, 130
d'Hendecourt L.B., Allamandola L.J., Grim R.J.A., Greenberg J.M.: 1986, *A&A*, 158, 119
d'Hendecourt L.B., Jourdain de Muizon M.: 1989, *A&A*, 223, L5
Donn B.: 1968, *ApJ*, 152, L129
Donn B., Nuth J.A.: 1985, *ApJ*, 288, 187
Dorschner J.: 1970, *Astron. Nachr.*, 292, 79
Dorschner J.: 1982, *Ap&SS*, 81, 323
Dorschner J., Henning T.: 1986, *Ap&SS*, 128, 47
Dorschner J., Schulze H.: 1993, *Astron. Gesellsch. Abstr. Ser.*, 9, 119
Dorschner J., Friedemann C., Gürtler J.: 1977, *Astron. Nachr.*, 298, 279
Dorschner J., Friedemann C., Gürtler J., Schielicke R.: 1984, *Bull. d' Information du Centre de Données Stellaires*, 27, 137
Dorschner J., Gürtler J., Henning T., Wagner H.: 1989, *Astron. Nachr.*, 310, 303
Dorschner J., Begemann B., Henning T., Jäger C., Mutschke H.: 1995, *A&A*, 300, 503
Draine B.T.: 1978, *ApJS*, 36, 595
Draine B.T.: 1984, *ApJ*, 277, L71
Draine B.T.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 313
Draine B.T.: 1990, in *The Evolution of the Interstellar Medium*, L. Blitz (ed.), San Francisco, A.S.P. Conference Series 12, p. 193
Draine B.T.: 1994, in *The Infrared Cirrus and Diffuse Interstellar Clouds*, R. Cutri, W.B. Latter (eds.), San Francisco, A.S.P. Conference Series 58, p. 227
Draine B.T., Lee, H.M.: 1984, *ApJ*, 285, 89
Draine B.T., McKee C.F.: 1993, *ARA&A*, 31, 373
Draine B.T., Malhotra S.: 1993, *ApJ*, 414, 632

Draine B.T., Sutin B.: 1987, *ApJ*, 320, 803
Ducati J.R.: 1986, *Ap&SS*, 126, 269
Duley W.W.: 1985, *MNRAS*, 215, 259
Duley W.W.: 1988, *Ap&SS*, 150, 387
Duley W.W.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p.141
Duley W.W.: 1993, in *Dust and Chemistry in Astronomy*, T.J. Millar, D.A. Williams (eds.), Institute of Physics Publishing, Bristol, p. 71
Duley W.W., Williams D.A.: 1993, *MNRAS*, 260, 37
Duley W.W., Williams D.A.: 1995, *MNRAS*, 272, 442
Dwek E. et al. 1986, in *Interrelationships Among Circumstellar, Interstellar, and Interplanetary Dust*, J. Nuth, R.E. Stencel (eds.), NASA CP 2403, WG-1
Dzegilenko F., Herbst E.: 1995, *ApJ*, 443, L81
Egan M.P., Leung C.M.: 1995, *ApJ*, 444, 251
Elmegreen B.G., Fiebig D.: 1993, *A&A*, 270, 397
Evans A.: 1994, *The Dusty Universe*, John Wiley Chichester
Fajardo-Acosta S.B., Telesco C.M., Knacke R.F.: 1993, *ApJ*, 417, L33
Fegley B. Jr., Prinn R.G.: 1989, in *The Formation and Evolution of Planetary Systems*, H.A. Weaver, L. Danly (eds.), Univ. Press Cambridge, Cambridge, p.171
Fischer O., Henning T., Yorke H.W.: 1995, *A&A*, in press
Fitzpatrick E.L., Massa D.: 1986, *ApJ*, 307, 286
Fitzpatrick E.L., Massa D.: 1990, *ApJS*, 72, 163
Freivogel P., Fulara J., Maier J.P.: 1994, *ApJ*, 431, L151
Frenklach M., Carmer C.S., Feigelson E.D.: 1989, *Nature*, 339: 196
Friedemann C., Gürtler J., Schmidt R., Dorschner J., 1981, *Ap&SS*, 79, 405
Furton D.G., Witt A.N.: 1992, *ApJ*, 386, 587
Geballe T.R., Joblin C., d'Hendecourt L.B., Jourdain de Muizon M., Tielens A.G.G.M., Léger A.: 1994, *ApJ*, 434, L15
Gehrz R.D.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 445.
Giard M., Lamarre J.M., Pajot F., Serra G.: 1994a, *A&A*, 286, 203
Giard M., Bernard J.P., Lacombe F., Normand P., Rouan D.: 1994b, *A&A*, 291, 239
Gillett F.C.: 1986, in *Light on Dark Matter*, F.P. Israel (ed.), D. Reidel, Dordrecht, p. 61
Glasse A.C.H., Towlson W.A., Aitken D.K., Roche P.F.: 1986, *MNRAS*, 220, 185
Goebel J.H.: 1993, *A&A*, 278, 226
Goebel J.H., Moseley S.H.: 1985, *ApJ*, 290, L35
Goebel J.H., Volk K., Walker H., Gerbault F., Cheeseman P., Self M., Stutz J., Taylor W.: 1989, *A&A*, 222, L5
Goebel, J.H., Bregman, J.D., Witteborn, F.C.: 1994, *ApJ*, 430, 317
Goldsmith P.F., Langer W.D., Wilson R.W.: 1986, *ApJ*, 303, L11
Gorti U., Bhatt H.C.: 1993, *A&A*, 270, 426
Greenberg J.M.: 1973, in *Interstellar Dust and Related Topics*, J.M. Greenberg, H.C. van de Hulst (eds.), Proc. IAU Symp. 52, D. Reidel, Dordrecht, p. 3
Greenberg J.M.: 1979, in *Stars and Stellar Systems*, B. Westerlund (ed.), D. Reidel, Dordrecht, p. 173
Greenberg J.M.: 1982, in *Submillimetre Wave Astronomy*, J.E. Beckman, J.P. Phillips (eds.), Cambridge Univ. Press, Cambridge, p. 261
Greenberg J.M.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 345
Greenberg J.M.: 1991, in *Chemistry in Space*, J.M. Greenberg, V. Pirronello (eds.), Kluwer, Dordrecht, p. 227
Greenberg J.M. (ed.): 1995, *The Cosmic Dust Connection*, Kluwer, Dordrecht, in press
Greenberg J.M., Yencha A.J.: 1973, in *Interstellar Dust and Related Topics*, J.M. Greenberg, H.C. van de Hulst (eds.), Proc. IAU Symp. 52, D. Reidel, Dordrecht, p. 369
Greenberg J.M., van de Bult C.E., Allamandola L.J., 1983, *J. Phys. Chem.*, 87, 4243
Grim R.J.A., Greenberg J.M.: 1987, *ApJ*, 321, L91.
Grim R.J.A., Baas F., Geballe T.R., Greenberg J.M., Schutte W.: 1991, *A&A*, 243, 473
Grün E., Zook H.A., Baguhl M., Balogh A., Bame S.J., Fechtig H., Forsyth R., Hanner M.S., Horanyi M., Kissel J., Lindblad B.A., Linkert D., Linkert G., Mann I., McDonnell J.A.M., Morfill G.E., Phillips

J.L., Polanskey C., Schwehm G., Siddique N., Staubach P., Svestka J., Taylor A.: 1993, *Nature*, 326, 428
Gürtler J., Henning T., Dorschner J., Friedemann C.: 1985, *Astron. Nachr.*, 306, 311
Gürtler J., Henning T., Dorschner J.: 1989, *Astron. Nachr.*, 310, 319
Hanner M.S.: 1995, *Highlights of Astronomy 10*, in press
Hanner M.S., Tokunaga A.T., Geballe T.R.: 1992, *ApJ*, 395, L111
Hanner M.S., Brooke T.Y., Tokunaga A.T.: 1994, *ApJ*, 433, L97
Hanner M.S., Brooke T.Y., Tokunaga A.T.: 1995, *ApJ*, 438, 250
Hartquist T.W., Williams D.A.: 1990, *MNRAS*, 247, 343
Hasegawa T.I., Herbst E.: 1993a, *MNRAS*, 261, 83
Hasegawa T.I., Herbst E.: 1993b, *MNRAS*, 263, 589
Hasegawa T.I., Herbst E., Leung C.M.: 1992, *ApJS*, 82, 167
Havnes O., Hartquist T.W., Pillip W.: 1987, in *Physical Processes in Interstellar Clouds*, G.E. Morfill, M. Scholer (eds.), D. Reidel, Dordrecht, p. 389
Hecht J.H.: 1986, *ApJ*, 305, 817
Hecht J.H.: 1991, *ApJ*. 367, 635
Heiles C., Kulkarni S.R.: 1987, in *Physical Processes in Interstellar Clouds*, G.E. Morfil, M. Scholer (eds.), D. Reidel, Dordrecht, p. 13
Henning T.: 1990, *Fund. Cosmic Physics*, 14, 321
Henning T.: 1995, in *Cosmic Dust Connection*, J.M. Greenberg (ed.), Kluwer, Dordrecht, in press
Henning T., Friedemann C., Gürtler J., Dorschner J.; 1984, *Astron Nachr.*, 305, 67
Henning T., Dorschner J., Gürtler J.: 1989, in *Interstellar Dust: Contributed Papers*, A.G.G.M. Tielens, L.J. Allamandola (eds.), NASA CP 3036, p. 395
Henning T., Begemann B., Mutschke H., Dorschner J.: 1995a, *A&AS*, 112, 143
Henning T., Chan J., Assendorp R.: 1995b, *A&A*, submitted
Henning T., Michel B., Stognienko R.: 1995c, *Planet. Space Sci.*, 43, in press
Herbig G.H.: 1995, *ARA&A*, 33, in press
Herbst E.: 1993, in *Dust and Chemistry in Astronomy*, T.J. Millar, D.A. Williams (eds.), Institute of Physics Publ., Bristol and Philadelphia, p. 183
Höfner S., Feuchtinger M.U., Dorfi E.A.: 1995, *A&A*, 297, 815
Hollenbach D., Salpeter E.E.: 1971, *ApJ*, 163, 155
Holm A.V., Wu C.C., Doherty L.R.: 1982, *PASP*, 94, 548
Hong S.S., Greenberg J.M.: 1978, *A&A*, 70, 695
Hoppe P., Amari S., Zinner E., Ireland T., Lewis R.S.; 1994, *ApJ*, 430, 870
Howard J.B., McKinnon J.T., Makarowsky Y., Lafleur A.L., Johnson M.E.: 1991, *Nature*, 352, 139
Hurwitz M., Bowyer S., Martin C.: 1991, *ApJ*, 372, 167
Huss G.: 1990, *Nature*, 347, 159
Huss G.R., Lewis R.S.: 1994, *Meteoritics*, 29, 791 and 811
Huss G.R., Lewis R.S.: 1995, *Geochim. Cosmochim. Acta*, 59, 115
Jäger C.: 1994, unpublished measurements
Jäger C., Mutschke H., Begemann B., Dorschner J., Henning T.: 1994, *A&A*, 292, 641
Jenkins E.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symposium 135, Kluwer, Dordrecht, p. 23
Jenniskens P., Greenberg J.M.: 1993, *A&A*, 274, 439
Jenniskens P., Désert F.-X.: 1993, *A&AS*, 106, 39
Jessberger E.K.: 1994, personal communication
Jones A.P., Tielens A.G.G.M.: 1994, in *The Cold Universe*, T. Montmerle. Ch.J. Lada, I.F.Mirabel, J.Trân Thanh Vân (eds.), Editions Frontières, Gif-sur-Yvette, p. 35
Jones A.P., Duley W.W., Williams D.A.: 1990, *QJRAS*, 31, 567
Jones A.P., Tielens A.G.G.M., Hollenbach D.J., McKee C.F.: 1994, *ApJ*, 433, 797
Jones B., Merrill K.M., Puetter R.C., Willner S.P.: 1978, *AJ*, 83, 1437
Jørgensen U.G.: 1988, *Nature*, 332, 702
Jourdain de Muizon M.: 1993, in *Astronomical Infrared Spectroscopy: Future Observational Directions*, S. Kwok (ed.), San Francisco, A.S.P. Conference Series 41, p. 79
Jourdain de Muizon M., Cox P., Lequeux J.: 1990, *A&ASS*, 83, 337
Jura M.: 1980, *ApJ*, 235, 63
Kerr T.H., Adamson A.J., Whittet D.C.B.: 1993, *MNRAS*, 262, 1047
Kim S.-H., Martin P.G.: 1995, *ApJ*, 444, 293

Kim S.-H., Martin P.G., Hendry P.D.: 1994, *ApJ*, 422, 164
Knacke R.F., Fajardo-Acosta S.B., Telesco C.M., Hackwell J.A., Lynch D.K., Russell R.W.: 1993, *ApJ*, 418, 440
Knude, J.: 1979, *A&A*, 77, 198
Knude J.: 1984, *NASA*, CP-2345, p. 123
Koike C., Kaito C., Yamamoto T., Shibai H., Kimura S., Suto H.: 1995, *Icarus*, 114, 203
Kozasa T., Hasegawa H.: 1987, *Prog. Theor. Phys.*, 77, 1402
Kozasa T., Dorschner J., Henning T., Stognienko R.: 1995. *A&A*, in press
Krätschmer W.: 1993, *J. Chem. Soc. Faraday Trans.*, 89, 2285
Krügel E., Chini R.: 1994, *A&A*, 287, 947
Krügel E., Siebenmorgen R.: 1994, *A&A*, 288, 929
Kwok, S. (ed.): 1993, *Astronomical Infrared Spectroscopy: Future Observational Directions*, San Francisco, A.S.P. Conference Series 41
Kwok S., Chan S.J.: 1993, *AJ*, 106, 2140
Kwok S., Volk K.M., Hrivnak B.J.: 1989, *ApJ*, 345, L51
Kwok S., Hrivnak B.J., Geballe T.R., Langill P.P.: 1993, in *Astronomical Infrared Spectroscopy: Future Observational Directions*, Kwok S. (ed.), San Francisco, A.S.P. Conference Series 41, 123
Lacy J.H., Baas F., Allamandola L.J., Perssons S.E. McGregor P.J., Lonsdale C.J., Geballe T.R., van de Bult C.E.P.: 1984, *ApJ*, 276, 533
Lagage P.O., Pantin E.: 1994, *The Messenger*, 75, 24
Lallement R., Bertin P.: 1992, *A&A*, 266, 479
Launhardt R. , Henning T.: 1995, in press
Léger A., Puget J.L.: 1984, *A&A*, 137, L5
Léger A., Jura M., Omont A.: 1985, *A&A*, 144, 147
Leitch-Devlin M.A., Williams D.A.: 1985, *MNRAS*, 213, 295
Lenzuni P., Gail H.-P., Henning T.: 1995, *ApJ*, p.447, 484
Lequeux J.: 1994, in *Molecules and Grains in Space*, I. Nenner (ed.), AIP Conf. Proc. 312, AIP Press, New York, p. 831
Lewis R.S., Tang M., Wacker J.F, Anders E., Steel E.: 1987, *Nature*, 326, 160
Lewis R.S., Anders E., Draine B.T.: 1989, *Nature*, 339, 117
Lewis R.S., Amari S., Anders E.: 1994, *Geochim. Cosmochim. Acta*, 58, 471.
Lis D.D., Leung C.M.: 1991, *ApJ*, 372, L107
Little-Marenin I.R.: 1986, *ApJ*, 307, L15
Little-Marenin I.R., Little S.J.: 1988, *ApJ* 333, 305
Little-Marenin I.R., Little S.J.: 1990, *AJ*, 99, 1173
Lorenz-Martins S., Lef'evre J.: 1994, *A&A*, 291, 831
Low F.J., Beintema D.A., Gautier T.N., Gillette F.C., Beichman C.A., Neugebauer G., Young E., Aumann H.H., Boggess N., Emerson J.P., Habing H.J., Hauser M.G., Houck J.R., Rowan-Robinson M., Soifer B.T., Walker R.G., Wesselius P.R.: 1984, *ApJ*, 278, L19
Markiewicz W.J., Mizuno H., Völk H.J., 1991, *A&A*, 242, 286
Martin P.G.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p.55
Martin P.G., Whittet D.C.B.: 1990, *ApJ*, 357, 113
Massa, D., Savage, B.D.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 3
Mathis J.S.: 1990, *ARA&A*, 28, 37
Mathis J.S.: 1993, *Rep. Prog. Phys.*, 56, 605
Mathis J.S.: 1994, *ApJ*, 422, 176
Mathis J.S., Whiffen G.: 1989, *ApJ*, 341, 808
Mathis J.S., Rumpl W., Nordsieck K.H.: 1977, *ApJ*, 217, 425 (MRN)
Mauersberger R., Wilson T.L., Mezger P.G., Gaume R., Johnston K.J.: 1992, *A&A*, 256, 640
McCarthy J.F., Forrest W.J., Briotta Jr. D.A., Houck J.R.: 1980, *ApJ*, 242, 965
McFadzean A.D., Whittet D.C.B., Longmore A.J., Bode M.F., Adamson A.J.: 1989, *MNRAS*, 241, 873
McKee C.F.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 431.
McKee C.F., Ostriker J.P.: 1977, *ApJ*, 218, 148
Mennella V., Colangeli L., Blanco A., Bussoletti E., Fonti S., Palumbo P., Mertins H.C.: 1995a, *ApJ*, 444, 288

Mennella V., Colangeli L., Bussoletti E., Monaco G., Palumbo P., Rotundi A.: 1995b, *ApJS*, p. 100, 149
Mendoza-Gómez C.X., de Groot M.S., Greenberg J.M.: 1995, *A&A*, 295, 479
Menshchikov S., Henning T.: 1995, *A&A*, in press
Mezger P.G., Sievers, A., Zylka R. et al.: 1992, *A&A*, 265, 743
Millar T.J., Williams D.A. (eds.): 1993, *Dust and Chemistry in Astronomy*, Inst. of Physics Publishing, Bristol
Mizuno H.: 1989, *Icarus*, 80, 189
Morfill G.E., Völk H.J.: 1984, *ApJ*, 287, 371
Murthy J., Dring A., Henry R.C., Kruk J.W., Blair W.P. Kimble R.A., Durrance S.T.: 1993, *ApJ*, 408, L97
Mutschke H., Begemann B., Dorschner J., Henning T.: 1994, *Infrared Phys. Technol.*, 35, 361
Mutschke H., Dorschner J., Henning T., Jäger C., Ott U.: 1995, *ApJ*, in press
Natta A., Prusti T., Krügel E.: 1993, *A&A*, 275, 527
Nejad L.A.M., Williams D.A.: 1992, *MNRAS*, 255, 441
Nenner I. (ed.): 1994, *Molecules and Grains in Space*, AIP Conf. Proc. 312, AIP Press, New York
Ney E.P.: 1977, *Science*, 195, 541
Nishi R., Nakano T., Umebayashi T.: 1991, *ApJ*, 368, 181
Nittler L., Alexander C.M. O'D., Gao X., Walker R.M., Zinner E.: 1994, *Nature*, 370, 443
Nittler L., Alexander C.M. O'D., Gao X., Walker R.M., Zinner E.: 1995, in *Nuclei in the Cosmos*, M. Busso, R. Gallino, and C. M. Raiteri (eds.), 3rd International Symposium on Nuclear Astrophysics. AIP, New York, p. 563
Norman C.A., Paresce F.: 1989, in *The Formation and Evolution of Planetary Systems*, H. Weaver, L. Danly (eds.), Univ. Press Cambridge, Cambridge, p. 151
Nuth J.A.: 1995, in *Cosmic Dust Connection*, J.M. Greenberg (ed.), Kluwer, Dordrecht, in press
Nuth J.A., Allen J.E.: 1992, *Ap&SS*, 196, 117
Nuth J., Donn B.: 1983, *Ap&SS*, 95, 175
Nuth III J.A., Hecht J. H.: 1990, *Ap&SS*, 163, 79
Nuth J.A., Moore M.H.: 1988, *ApJ*, 329, L113
Nuth J.A., Moseley S.H., Silverberg R.F., Goebel J.H., Moore W.H.: 1985, *ApJ*, 290, L41
Nuth, J.A., Nelson, R.N., Moore, M., Donn, B.: 1988, in *Experiments on Cosmic Dust Analogues*, E. Bussoletti, C. Fusco, G. Longo (eds.), Kluwer, Dordrecht, p. 191
Ogmen M., Duley W.W.: 1988, *ApJ*, 334, L117
Olnon F.M., Raimond E. (eds.): 1986, *A&AS*, 65, 607
Omont A.: 1991, in *Chemistry in Space*, J.M. Greenberg, V. Pirronello (eds.), Kluwer, Dordrecht, p. 171
Omont A.: 1993, in *Astronomical Infrared Spectroscopy: Future Observational Directions*, S. Kwok (ed.), San Francisco, ASP Conf. Ser. Vol. 41, p. 87
Omont A., Moseley S.H., Forveille T., Harvey P.M., Glaccum W.J., Likkel L.: 1990, *ApJ*, 355, L27
Omont A., Cox P., Moseley S.H., Glaccum W., Casey S., Forveille T., Szczerba R., Chan K.-W.: 1994, in *From Gas to Stars to Dust*, M.R. Haas, J.A. Davidson, E.F. Erickson (eds.), in press
Omont A., Moseley S.H., Cox P., Glaccum W., Casey S., Forveille T., Chan K.-W., Szczerba R., Loewenstein R.F., Harvey P.M., Kwok S.: 1995, *ApJ*, in press
Onaka T., de Jong T., Willems F.J.: 1989, *A&A*, 218, 169
Oort J. H., van de Hulst H.C.: 1946, *Bull. Astron. Inst. Netherlands*, 10, 187
Ossenkopf V.: 1991, *A&A*, 251, 210
Ossenkopf V.: 1993, *A&A*, 280, 617
Ossenkopf V., Henning T.: 1994, *A&A*, 291, 943
Ott U.: 1993a, in *Protostars and Planets III*, E.H. Levy, J.I. Lunine (eds.), Univ. Arizona Press, Tucson, Ariz., p. 883
Ott U.: 1993b, *Nature*, 364, 25
Oudmaijer R.D., de Winter D.: 1995, *A&A*, 295, L43
Palumbo M.E., Strazzulla G.: 1993, *A&A*, 269. 568
Paresce F., Artymowicz P.: 1989, in *Structure and Dynamics of the ISM*, G. Tenorio-Tagle, M. Moles, J. Melnick (eds.), Springer, Berlin, p. 221
Paresce F., Burrows C.: 1987, *ApJ*, 319, L23
Patten B.M., Willson L.A.: 1991, *AJ*, 102, 323
Pendleton Y.J., Sandford S.A., Allamandola L.J., Tielens A.G.G.M., Sellgren K.: 1994, *ApJ*, 437, 683
Pirronello V.: 1993, in *Dust and Chemistry in Astronomy*, T.J. Millar, D.A. Williams (eds.), Institute of Physics Publ., Bristol and Philadelphia, p. 297
Preibisch T., Ossenkopf V., Yorke H.W., Henning T.: 1993, *A&A*, 279, 577

Prinn R.G.: 1993, in *Protostars and Planets III*, E.H. Levy, J.I. Lunine (eds.), Univ. Arizona Press, Tucson, p. 1005
Puget L.J., Léger A.: 1989, *ARA&A*, 27, 161
Rietmeijer F.J.M.: 1992, *ApJ*, 400, L39
Ristorcelli I., Giard M., Mény C., Serra G., Lamarre J.M., Le Naour C., Léotin J., Pajot F.: 1994, *A&A*, 286, L23
Roche P.F.: 1988, in M.E. Bailey, D.A. Williams (eds.), Dust in the Universe, Cambridge Univ. Press, Cambridge, p. 415
Rowan-Robinson M., Harris S.: 1982, *MNRAS*, 200: 197
Rowan-Robinson M.: 1992, *MNRAS*, 258, 787
Russell S.S., Arden J.W., Pillinger C.T.: 1991, *Science*, 254, 1188
Sakata A., Wada S.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symposium 135, Kluwer, Dordrecht, p. 191
Salama F., Allamandola L.J.: 1992, *ApJ*, 395, 301
Salama F., Allamandola L.J.: 1993, *J. Chem. Soc. Faraday Trans.*, 89, 2277
Sandford S.A., Allamandola L.J., Tielens A.G.G.M., Sellgren K., Tapia M., Pendleton Y.: 1991, *ApJ*, 371, 607
Sandford S.A., Allamandola L.J., Geballe T.R.: 1993, *Science*, 262, 400
Sandford S.A., Pendleton Y.J., Allamandola L.J.: 1995, *ApJ*, 440, 697
Saslaw W.C., Gaustad J.E.: 1969, *Nature*, 221, 160
Schutte W.A.: 1988, PhD Thesis, Leiden University
Schutte W.A., Greenberg J.M.: 1991, *A&A*, 244: 190
Schweitzer J.S.: 1978, *ApJ*, 225, 116
Seab C.G.: 1987, in *Interstellar Processes*, D.J. Hollenbach, H.A. Thronson Jr. (eds.), D. Reidel, Dordrecht, p.491
Seaton M.S.: 1979, *MNRAS*, 187, 73P
Sedlmayr, E: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 467.
Sedlmayr E.: 1994, in *Molecules in the Stellar Environment*, U.G. Jørgensen (ed.), Springer, Berlin, p. 163
Sellgren K.: 1984, *ApJ*, 277, 623
Sellgren K.: 1989, in *Interstellar Dust*, L.J. Allamondola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer Acad. Press, Dordrecht, p. 103
Sellgren K.: 1990, in *Dusty Objects in the Universe*, E. Bussoletti, A.A. Vittone (eds.), Kluwer, Dordrecht, p.35
Sellgren K.: 1994, in *The Infrared Cirrus and Diffuse Interstellar Clouds*, R. Cutri, W.B. Latter (eds.), San Francisco, A.S.P. Conference Series 58, p. 243
Sellgren K., Werner M.W., Dinerstein H.L.: 1983, *ApJ*, 271, L13
Sellgren K., Allamandola L.J., Bregman J.D., Werner M.W., Wooden D.H.: 1985, *ApJ*, 299, 416
Sellgren K., Smith R.G., Brooke T.Y.: 1994, *ApJ*, 433, 179
Serkowski K.: 1973, in *Interstellar Dust and Related Topics*, J.M. Greenberg, H.C. van de Hulst (eds.), Proc. IAU Symposium 52, D. Reidel, Dordrecht, p. 145
Serkowski K., Mathewson D.S., Ford V.L., 1975, *ApJ*: 196, 261
Shalabiea O.M., Greenberg J.M.: 1995, *A&A*, p. 296, 779
Shull J.M.: 1987, in *Interstellar Processes*, D.J. Hollenbach, H.A. Thronson Jr. (eds.), D. Reidel, Dordrecht, p. 225
Shull J.M., Draine B.T.: 1987, in *Interstellar Processes*, D.J. Hollenbach, H.A. Thronson Jr. (eds.), D. Reidel, Dordrecht, p.283
Siebenmorgen R.: 1993, *ApJ*, 408, 218
Siebenmorgen R., Krügel E.: 1992, *A&A*, 259, 614
Simpson J.P.: 1991, *ApJ*, 368, 570
Sitko M.L., Halbedel E.M., Lawrence G.F., Smith J.A., Yanow K.: 1994, *ApJ*, 432, 753
Skinner C.J., Whitmore B.: 1988, *MNRAS*, 234, 79p
Skinner C.J., Griffin I., Whitmore B.: 1990, *MNRAS*, 243, 78
Skinner C.J., Tielens A.G.G.M., Barlow M.J., Justtanont K.: 1992, *ApJ*, 399, L79
Skinner C.J., Sylvester R.J., Graham J.R., Barlow M.J., Meixner M., Keto E., Arens J.F., Jernigan J.G., 1995; *ApJ*, p. 444, 861
Slavin J.D.: 1989, *ApJ*, 346, 718
Smith B.A., Terrile R.J.: 1984, *Science*, 226, 1421

Smith R.G.: 1993, *MNRAS*, 264, 587
Smith R.G., Sellgren K., Tokunaga, A.T.: 1989, *ApJ*, 344, 413
Smith R.G., Sellgren K., Brooke T.Y., 1993, *MNRAS*, 263, 749
Sodroski T.J., Dwek E., Hauser M.G., Kerr F.J.: 1989, *ApJ*, 336, 762
Sodroski T.J., Bennett C., Boggess N., Dwek E., Franz B.A., Hauser M.G., Kelsall T., Moseley S.H., Odegard N., Silverberg R.F., Weiland J.L.: 1994, *ApJ*, 428, 638
Sofia U.J., Cardelli J.A., Savage B.D.: 1994, *ApJ*, 430, 650
Sorrell W.F.: 1990, *MNRAS*, 243, 570
Sorrell W.F.: 1991, *MNRAS*, 248, 439
Sorrell W.F.: 1992, *MNRAS*, 255, 594
Stencel R.E., Nuth III J.A., Little-Marenin I.R.: 1990, *ApJ*, 350, L45
Sterzik M.F., Morfill G.E.: 1994, *Icarus*, 111, 536
Stognienko R., Henning T., Ossenkopf V.: 1995, *A&A*, 296, 797
Strazzulla G., Baratta G.A.: 1992, *A&A*, 266, 434
Strom, K.M., Strom, S.E., Merrill K.M.: 1993a, *ApJ*, 412, 233
Strom S.E., Edwards S., Skrutskie M.F.: 1993b, in *Protostars and Planets III*, E.H. Levy, J.I. Lunine (eds.), Univ. Arizona Press, Tucson, p.837
Suto H., Mizutani K., Maihara T.: 1992, *AJ*, 103, 927
Sylvester R.J., Barlow M.J., Skinner C.J.: 1994, *MNRAS*, 266, 640
Sylvester R.J., Barlow M.J., Skinner C.J.: 1995, *ApJ*, in press
Tanaka M., Sato S., Nagata T., Yamamoto T.: 1990, *ApJ*, 352, 724
Tapia M., Persi P., Roth M., Ferrari-Toniolo M.: 1989, *A&A*, 225, 488
Tegler S.C., Weintraub, D.A., Allamandola L.J., Sandford S.A., Rettig T.W., Campins H.: 1993, *ApJ*, 411, 260
Tegler S.C., Weintraub D.A., Rettig T.W., Pendleton Y.J., Whittet D.C.B., Kulesa C.A.: 1995, *ApJ*, 439, 279
Thaddeus P.: 1994, in *Molecules and Grains in Space*, I. Nenner (ed.), AIP Conf. Proc. 312, AIP Press, New York, p.711
Thompson S.P., Evans A., Jones A.P.: 1995, *A&A*, in press
Tielens A.G.G.M.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), IAU Symp. 135, Kluwer, Dordrecht, p.239
Tielens A.G.G.M.: 1990a, in *From Miras to Planetary Nebulae: Which Path for Stellar Evolution?* M.O. Mennessier, A. Omont (eds.), Editions Frontières, p.186
Tielens A.G.G.M.: 1990b, in *Carbon in the Galaxy: Studies from Earth and Space*, J.C. Tarter, S. Chang, D.J. DeFrees (eds.), NASA CP 3061, p.59
Tielens A.G.G.M., Allamandola L.J.: 1987, in *Interstellar Processes*, D.J. Hollenbach, H.A. Thronson Jr. (eds.), D. Reidel, Dordrecht, p.397
Tielens A.G.G.M., Snow T.P. (eds.): 1995, *The Diffuse Interstellar Bands*, Kluwer, Dordrecht, in press
Tielens A.G.G.M., Seab C.G., Hollenbach D.J., McKee C.: 1987, *ApJ*, 319, L109
Tielens A.G.G.M., Tokunaga A.T., Geballe T.R., Baas F.: 1991, *ApJ*, 381, 181
Tielens A.G.G.M., McKee, C.F., Seab C.C., Hollenbach D.H.: 1994, *ApJ*, 431, 321
Timmermann R., Larson H.P.: 1993, *ApJ*, 415, 820
Tinbergen J.: 1982, *A&A*, 105, 53
Ugarte D.: 1992, *Nature*, 359, 707
Ugarte D.: 1993, *Europhys. Lett.*, 22, 45
Ugarte D.: 1995, *ApJ*, 443, L85
Umebayashi T., Nakano T.: 1990, *MNRAS*, 243, 103
van Dishoeck E.F., Blake G.A., Draine B.T., Lunine J.I.: 1993, in *Protostars and Planets III*, E.H. Levy, J.I. Lunine, M.S. Matthews (eds.), Univ. Arizona Press, Tucson, p. 163
Vardya M.S., de Jong T., Willems F.J.: 1986, *ApJ*, 304, L29
Virag A., Zinner E., Lewis R.S., Tang M.: 1989, *Lunar Plan. Sci.*, 20, 1158
Vrba F.J., S.J. Coyne G.V., Tapia S.: 1993, *AJ*, 105, 1010
Walker H.J., Wolstencroft R.D.: 1988, *PASP*, 100, 1509
Walmsley C.M.: 1991, in *Fragmentation of Molecular Clouds and Star Formation*, E. Falgarone, F. Boulanger, G. Duvert (eds.), IAU Symp. 147, Kluwer Academic Publ., Dordrecht, p.161
Walmsley C.M., Schilke P.: 1993, in *Dust and Chemistry in Astronomy*, T.J. Millar, D.A. Williams (eds.), Institute of Physics Publ., Bristol and Philadelphia, p. 37
Ward-Thompson D., Robson E.I., Whittet D.C.B. et al.: 1989, *MNRAS*, 241, 119

Weintraub D.A., Tegler S.C., Kastner J.H., Rettig T.: 1994, *ApJ*, 423, 674
Whittet D.C.B.: 1984, *MNRAS*, 210, 479
Whittet D.C.B.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 455
Whittet D.C.B.: 1992, *Dust in the Galactic Environment*, Inst. of Physics Publishing, Bristol, p. 193
Whittet D.C.B.: 1993, in *Dust and Chemistry in Astronomy*, T.J. Millar, D.A. Williams (eds.), Institute of Physics Publ., Bristol and Philadelphia, p. 9
Whittet D.C.B., Duley W.W.: 1991, *AAR*, 2, 167
Whittet D.C.B., Walker H.J.: 1991, *MNRAS*, 252, 63
Whittet D.C.B., Bode M.F., Longmore A.J., Adamson A.J., McFadzean A.D., Aitken D.K., Roche P.F.: 1988, *MNRAS*, 233, 321
Whittet D.C.B., Duley D.D., Martin P.G.: 1990, *MNRAS*, 244, 427
Whittet D.C.B., Martin P.G., Hough J.H., Rouse M.F., Bailey J.A., Axon D.J.: 1992, *ApJ*, 386, 562
Willacy K., Williams D.A.: 1993, *MNRAS*, 260, 635
Willacy K., Williams D.A., Duley W.W.: 1994, *MNRAS*, 267, 949
Willems F.J., de Jong T.: 1986, *ApJ*, 309, L39
Willems F.J., de Jong T.: 1988, *A&A*, 196, 173
Williams D.A.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp. 135, Kluwer, Dordrecht, p. 367
Williams D.A., Hartquist T.W., Whittet D.C.B.: 1992, *MNRAS*, 258, 599
Williams P.M., van der Hucht K.A., Thé P.S.: 1987, *A&A*, 182, 91
Witt A.N.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symp.135, Kluwer, Dordrecht, p. 87
Witt A.N., Boroson T.A.: 1990, *ApJ*, 355, 182
Witt A.N., Schild R.E.: 1988, *ApJ*, 325, 837
Witt A.N., Bohlin R.C., Stecher T.P.: 1986, *ApJ*, 305, L23
Witt A.N., Bohlin R.C., Stecher T.P., Graff S.M.: 1987, *ApJ*, 321, 912
Witt A.N., Petersohn J.K., Bohlin R.C., O'Connell R.W., Roberts M.S., Smith A.M., Stecher T.P.: 1992, *ApJ*, 395, L5
Wolff M.J., Clayton G.C., Meade M.R.: 1993, *ApJ*, 403, 722
Wolfire M.G., Churchwell E.: 1994, *ApJ*, 427, 889
Wooden D.H., Rank D.M., Bregman J.D., Witteborn, F.C., Tielens A.G.G.M., Cohen M., Pinto P.A., Axelrod T.S., 1993, *ApJS*, 88, 477
Wright E.: 1989, in *Interstellar Dust*, L.J. Allamandola, A.G.G.M. Tielens (eds.), Proc. IAU Symposium 135, Kluwer, Dordrecht, p. 337
Wright E.L., Mather J.C., Bennett C.L., Cheng S., Shafer R.A., Fixsen D.J., Eplee Jr. R.E., Isaacman R.B., Read S.M., Boggess N.W., Gulkis S., Hauser M.G., Janssen M., Kelsall T., Lubin P.M., Meyer S.S., Moseley Jr. S.H., Murdock T.L., Silverberg R.F., Smoot G.F., Weiss R., Wilkinson D.T.: 1991, *ApJ*, 381, 200
Yorke H.W.: 1986, *ARA&A*, 24, 48
Zavagno A., Cox P., Baluteau J.-P.: 1992, *A&A*, 259, 241
Zinner E.: 1995, in *Nuclei in the Cosmos*, M. Busso, R. Gallino, C.M. Raiteri (eds.), 3rd International Symposium on Nuclear Astrophysics, AIP Press, New York, p. 546
Ziurys L.M., Snell R.L.,Dickman R.L.: 1989, *ApJ*, 341, 857

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