

Dust from AGB stars

Anja C. Andersen

*Dark Cosmology Centre, Niels Bohr Institute, University of
Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark.
Email: anja@dark-cosmology.dk*

Abstract. Dust is formed in the expanding atmosphere during late stages of stellar evolution. Dust influences the dynamics and thermodynamics of the stellar atmosphere by its opacity. The dust opacity depends both on the optical properties of the grain material as well as on the amount of dust present. A rich source of information on some mineral phases of dust in AGB stars comes from the study of presolar grains from meteorites. This paper presents a short overview of presolar grains studies and describes how the optical properties of dust grains are obtained in the laboratory.

1. Dust and AGB stars

The formation of molecules and dust grains is strongly dependent on the time-dependent dynamical processes that affect the atmospheres of AGB stars, i.e. pulsations and propagating shock waves.

Two basic conditions must be fulfilled in the AGB star atmosphere for dust formation to succeed, relatively low temperature (< 2000 K) combined with high density. The sufficiently low temperature is present above the photosphere. As a consequence of the pulsation, the outer atmosphere is levitated, resulting in a temporary reservoir of relatively dense gas at a certain distance from the photosphere, and thus increasing the efficiency of dust formation.

Observations indicate that dust is a significant ingredient of the outflows from AGB stars. It has therefore long been assumed that the mass loss from AGB stars is driven by radiation pressure on dust grains (e.g. Heras & Hony 2005), however, recent frequency-dependent numerical models of M-type stars have not yet been able to support this (see Höfner and Woitke in these proceedings).

In this paper the focus is on what we know about the dust properties from studies of presolar AGB dust grains from meteorites, and from laboratory studies of dust analogues.

2. Dust from AGB stars - Presolar grains extracted from meteorites

While most of the material that went into the making of the Solar System was thoroughly processed and mixed, thus losing isotopic heterogeneity and all memory of its origin, small quantities of refractory dust grains survived the events that led to the formation of the Solar System and such grains have been

found in primitive meteorites (Zinner 1998; Hoppe & Zinner 2000; Nittler et al. 2003; Zinner 2004; Hoppe & Ott 2007) .

When the matrix material from these primitive meteorites was heated in the laboratory, it was realized already in the early 1960'ies that at certain temperatures the matrix released noble gases with an isotopic composition markedly different from everything else in the Solar System. Although the noble gasses are far less abundant than condensable elements, they are present in measurable quantities in virtually all meteorites. Isotopic variations in noble gases are quite often orders of magnitudes larger than the isotopic variations in the rock-forming elements, because even the most primitive bulk meteorites contain only a small fraction ($\approx 10^{-4}$ for Xe and $\approx 10^{-9}$ for He) of their Solar abundances. This means that the noble gases are less contaminated by “normal” matter, than other more abundant elements. It was quickly realized that in view of the volatility of these gases, they must be trapped in solid grains. The carrier should be a refractory mineral which would be chemically resistant under the conditions prevailing in the interstellar medium, during formation of the Solar System and evolution of the meteorite parent body. Based on these requirements, two forms of matter can be expected to have survived and to be identifiable as presolar: refractory oxides and refractory carbon compounds, which are the chemically stable forms for different carbon to oxygen (C/O) ratios. For the Solar System ratio of C/O = 0.42 (Anders & Grevesse 1989), the oxides, not the carbon compounds, are the stable phase.

After years of trials with different chemical purification of the matrix material, and subsequent stepwise heating and isotopic noble gas measurements, the first presolar grains were finally isolated by Lewis et al. (1987), and identified as tiny diamonds. Later silicon carbide (SiC) (Bernatowicz et al. 1987), graphite (Amari et al. 1990), corundum (Al_2O_3) (Hutcheon et al. 1994; Nittler et al. 1994), silicon nitride (Si_3N_4) (Russell et al. 1995; Nittler et al. 1995) and spinel (MgAl_2O_4) (Nittler et al. 1994) were identified. Some of the SiC and graphite grains have been found to carry small inclusions of Ti-, Mo- and Zr-carbides (Bernatowicz et al. 1991).

Central to the identification of presolar grains is the determination of the isotopic composition of the grain and/or some trace elements trapped in the grains. As a rule the isotopic composition of the grain or some of its inclusions deviates strongly from the normal Solar System composition. The isotopic signatures of the grains contain information of the nucleosynthesis processes of the parent stars. Information on individual stars can be obtained by studying single grains by e.g. SIMS (Secondary Ion Mass Spectrometry) for the light to intermediate-mass elements, RIMS (Resonance Ionization Mass Spectrometry) for the heavy elements, and laser heating and gas mass spectrometry for He and Ne. TEM (Transmission Electron Microscopy) and SEM (Scanning Electron Microscopy) is used to study the crystal structure of the individual grains.

Diamonds account for more than 99% of the identified presolar meteoritic material, with an abundance that can exceed 0.1% (1000 ppm) of the matrix (Huss & Lewis 1995), corresponding to more than 3% of the total amount of carbon in the meteorite. Silicates are the second most abundant of the identified presolar grains. There seem to be two distinct groups of oxides and silicates, one originating from RGB stars and one from AGB stars. Identification of presolar

silicates is complicated as they are “diluted” by the sea of “normal silicates” formed in the solar nebular, and analysis have therefore first begun to really develop with the new NanoSIMS technique (e.g. Hoppe et al. 2004) which allows an imaging search for isotopically anomalous phases *in situ* in the matrix of the meteorites.

The best characterized of the presolar grains are SiC (6 ppm) and almost all of the presolar SiC grains originate from AGB stars. Graphite (less than 1 ppm) was traditionally assumed to originate from supernovae, but recent measurements of *s*-process signatures indicate that most high-density graphite grains are more likely to originate from AGB stars (Croat et al. 2005).

Table 1. Results of isotopic analyses on presolar grains. Data taken from Ott (1993) and Hoppe & Ott (2007).

Mineral	Analysis type	Isotopic Anomalies	Abund. (\sim ppm)	Grain size (μm)
Diamond	Bulk	Noble gases, N, Sr, Ba	1500	0.002 – 0.003
Silicon Carbide	Single grain Bulk	C, N, Si, Mg–Al, Ti, Ca, He, Ne Noble gases, Sr, Ba, Nd, Sm, Dy, Er	30	0.1 – 30
Graphite	Single grain Bulk	C, N, Mg–Al, O, Si, Ca, Ti, He, Ne Noble gases	1	0.1 – 10
Oxides	Single grain	O, Al–Mg, Ti	50	0.1 – 5
Silicates	Single grain	O, Al–Mg, Ti	140	0.1 – 1
Silicon Nitride	Single grain	C,N,Si	1	0.002

Correlated measurements of as many elements as possible for a given grain are of special importance because such data makes it possible to set much tighter constraints on stellar sources and models of nucleosynthesis. In some cases, correlated measurements make it possible to construct stellar histories of individual grains (Huss et al. 1997).

Observational data from both stars and presolar grains have clearly demonstrate the existence of “cool bottom burning” (Wasserburg et al. 1995) occurring in low-mass RGB and AGB stars.

Presolar grains hold great promise for improving our understanding of dust grain nucleation and growth in stellar environments, since formation processes are recorded in the detailed structures and compositions of the grains that can be characterized in minute detail. For instance, different types (masses/metallicities) of AGB stars seem to produce SiC grains with similar size distributions, which very likely reflects some common underlying mechanism.

Formation of grains that range in size from 100 nm or less to several microns seems to require a range of gas densities in outflows. In particular, formation of large ($>1 \mu\text{m}$) AGB grains on reasonable time-scales requires higher densities (Nuth et al. 2006) than models indicate. The density variations recorded by the grains could be caused by shocks in the outflows that are observed astronomically, and might highlight the need for two- and three-dimensional models of grain growth in outflows (Bernatowicz et al. 2005), or that pulsations will bring

the materials to favorable growth sites (sweet spots) where grains can stay for long enough time periods to grow larger than the average grain size.

As presolar grains seem to come from many stellar sources and to be relatively unprocessed, they also provide constraints on circumstellar dust production rates in the Galaxy. The relative abundances of the different types of presolar grain seem to indicate that AGB stars are the main dust producers in the Galaxy, while supernovae only contribute a few percent (Alexander 1997).

3. Measuring optical properties of AGB dust analogues in the lab

A particle placed in a beam of light will scatter some of the light incident on it (i.e. the light will change direction) and absorb some of the light (i.e. the electromagnetic energy is transformed into other forms of energy by the particle). We say that the light has suffered extinction. The amount of light scattered and/or absorbed by the particle depends on the exact nature of the particle and also on the nature of the incident light. Consequently the extinction is dependent on the chemical composition of the particle and its size, shape and orientation, together with the wavelength and polarisation state of the light. The treatment of absorption and scattering of light by dust particles is a complicated problem within electromagnetic theory. For a comprehensive description see e.g. Bohren & Huffman (1983).

Rayleigh (1871) developed the scattering theory for light scattered by dust particles with diameters smaller than the wavelength of the incident light, and showed that the amount of scattering is inversely proportional to the fourth power of the wavelength (λ^{-4}). This means that the shorter the wavelength of the incident light, the more the light is scattered. When the dimensions of the dust particles increase, the λ^{-4} law ceases to be valid. Dispersion is then less selective with respect to λ , and Mie scattering theory (Mie 1908) should be used. The complete formalism is sometimes referred to as Lorenz-Mie theory due to the previous work carried out by the Danish scientist Ludvig Lorenz (Kragh 1991). A complementary solution based on expansions of scalar potentials was given by Debye (1909). Mie theory is more generally valid and contains Rayleigh scattering as an approximation for particles small compared to the wavelength, and geometrical optics as an approximation for particles large compared with the wavelength. For sufficiently large dust particles, the dispersion of radiation approaches a $1/\lambda$ dependence, leading to diffuse reflection.

There are no analytic solutions of the light scattering problem for particles of arbitrary shape, but in many cases, spectra of irregular particles can be approximated by a suitably averaging over different ellipsoidal shape parameters. With these approximations it is possible to obtain simple expressions for an average extinction cross section.

The simplest approximation is that for spheres. Another approximation is a collection of randomly oriented ellipsoidal particles of all ellipticities (from spheres to infinite long needles). This continuous distribution of ellipsoids (CDE) was introduced by Bohren & Huffman (1983). Ossenkopf et al. (1992) have introduced a distribution with a higher probability for spheres (m-CDE), and being zero for the extreme values corresponding to infinitely thin needles or

flattened pancakes. Calculations of the three different grain shape distributions, spheres, CDE and m-CDE for SiC grains can be seen in Mutschke et al. (1999).

The two sets of quantities that are used to describe optical properties of dust particles are the real and imaginary parts of the complex refractive index $m = n + ik$ or the real and imaginary parts of the complex dielectric function (or relative permittivity) $\epsilon = \epsilon' + i\epsilon''$. These two sets of quantities are not independent; $\epsilon \equiv m^2$. The pair of quantities n and k are referred to as the optical constants, a bit misleading since they are frequency-dependent.

For dust particles which are small compared to the wavelength, there are two distinct energy ranges in which resonances occur. One is in the infrared, in the region of strong lattice bands between the transverse optical phonon frequency (ω_{TO}) and the longitudinal optical phonon frequency (ω_{LO}). The other is in the ultraviolet and is due to the transitions of bound electrons. The optical properties corresponding to electronic transitions in condensed matter are in many cases described qualitatively correct by an oscillator model. The oscillator model is often used to derive n and k from reflection measurements of bulk materials.

To obtain the optical properties of dust particles, there are two approaches. Either the optical constants can be determined by reflection and/or transmission measurements of bulk samples (e.g. single crystal, thin film or equivalent) and small-particle spectra can be calculated from these. Or transmission measurements can be performed on samples of individual particles. Both methods have pros and cons.

By determining n and k from bulk samples, it is assumed that the optical properties of the material can be completely specified. Therefore it is necessary to make assumptions of the grain size and morphology in-order to derive the optical properties of grains from the measurement of the particular material. Different assumptions about grain size and shape lead to very different spectral appearance.

By measuring on samples of individual particles on the other hand, the grains have a certain size and morphology which of course should resemble what is expected of cosmic grains. In space, grains will appear as single isolated particles in vacuum. To simulate this in the laboratory the grains are dispersed in a solid matrix which is transparent in the desired wavelength region. However, in the matrix there is a tendency of the grain sample to clump, which will result in a spectrum of small clusters of grains, which might be very different from a spectrum of single isolated particles. On top of this, the fact that the matrix has a refractive index different from vacuum will influence the band shape, see Mutschke et al. (1999) and Papoular et al. (1998) for a discussion of matrix effects.

From a measurement of a particle sample, the extinction efficiency factor, Q_{ext} , can be directly determined by a transmission measurement. In principle it is possible to determine n and k from the feature of a transmission (or absorption) measurement. But this is only a quantitative method *if* the path length is known and the medium is homogeneous. With the present method of obtaining laboratory spectra of particles embedded in a matrix, the assumption of a homogeneous medium will sometimes be far from reality. Clustering can cause a dramatic difference in the optical properties (Huffman 1988).

This leaves the astronomer in a dilemma: Is it better to use n and k from bulk measurements or samples of individual particles included in a matrix measurement, when wanting to compare with observed astronomical spectra? There is no simple answer to this question and “the solution” will in many cases depend on the available laboratory data. The choice is to either use data of realistic grains, but possible agglomerated, or to use n and k from bulk measurements, for calculations of idealised grains in vacuum. A list of laboratory data (both bulk and particulate) can be found in the database by Henning et al. (1999), where a broad collection of laboratory measurements from various scientific journals and handbooks has been compiled.

4. Dust formed in C-rich AGB stars

While carbon is expected to constitute a major fraction of the circumstellar dust in carbon stars, its mineralogical form is still unclear. Carbon has the unique property that the atoms can form three different types of bonds through sp^1 , sp^2 (graphite) and sp^3 (diamond) hybridization. Amorphous carbon is a broad term covering materials which have a combination of the different bond types.

A number of observations of carbon-rich late-type stars indicate that amorphous carbon is the dominant dust type in these stars (e.g. Campbell et al. 1975; Sopka et al. 1985; Martin & Rogers 1987; Gurtler et al. 1996).

Amorphous materials can show a whole range of different optical properties, related to the exact micro-physical properties of the measured sample. Amorphous carbon is an illustrative example of this, as the measured extinction can differ by a factor of 10 (see Fig. 1) depending on the detailed micro-physical properties of the amorphous dust.

Amorphous carbon grains are apparently a good candidate as the common type of carbon grains present in circumstellar envelopes, but again the astronomer is left with a dilemma: Which of the available laboratory data should one choose when they differ so much? Unless there is some indication from observations on which of the amorphous carbon laboratory data best represent the stellar conditions, it isn’t easy to say. Andersen et al. (2003) have demonstrated that although using one or the other of the amorphous dust data presented in Fig. 1 didn’t make a big difference for the hydrodynamic model structure, it had significant influence in the radiative transfer calculations and thereby influenced the spectral energy distribution estimated for the circumstellar dust shell.

Thermodynamic equilibrium calculations performed by Friedemann (1969a,b) and Gilman (1969) suggested that SiC particles can form in the mass outflow of C-rich AGB stars. The observations performed by Hackwell (1972) and Treffers (1974) presented the first observational evidence for the presence of SiC particles in stellar atmospheres. A broad infrared emission feature seen in the spectra of many carbon stars, peaking between 11.0 and 11.5 μm is attributed to solid SiC particles and SiC is believed to be a significant constituent of the dust around carbon stars.

Some years ago there was a lot of confusion as to whether the crystal structure of SiC could be identified from spectra of C-stars, but laboratory measurements have now shown this is not possible, as the crystal structure is not as

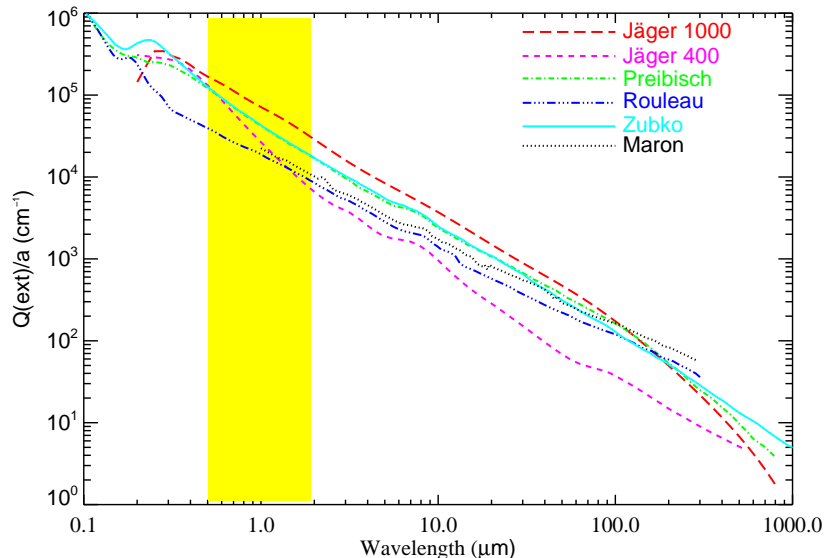


Figure 1. Calculated extinction efficiency, Q_{ext} over particle radius, a , of amorphous carbon from optical constants published by Maron (1990), Rouleau & Martin (1991), Preibisch et al. (1993), Zubko et al. (1996) and two different samples (cel1000 and cel400) from Jäger et al. (1998). The Jäger 1000 sample contains significantly more sp^2 bonds than the Jäger 400 sample. The extinction efficiency factors were calculated from the optical constants (n and k) in the Rayleigh approximation for spheres. The shaded area indicate the wavelength region of maximum flux for typical AGB photospheres.

significant as the morphology of the SiC grains. See Mutschke et al. (1999) for details.

One of the main reasons for the huge mass loss of carbon-rich AGB stars seems to be the presence of newly formed dust grains. The strong shock waves in the stellar atmosphere cause a levitation of the outer layers. The cool and relatively dense environment which results from the levitation provides favorable conditions for the formation of molecules and grains. Due to its high opacity and the resulting radiative pressure, dust plays an important role in driving the wind.

5. Dust formed in O-rich AGB stars

Magnesium-iron silicates have been found around evolved stars with an oxygen-rich dusty outflow (e.g. Waters et al. 1996; Sylvester et al. 1999; Molster et al. 2002), as well as around stars with carbon-rich chemistry (e.g. Waters et al. 1998). Only a fraction ($\sim 10\%$) of the observed silicates are in crystalline form (Kemper et al. 2001).

Silicates are the most stable condensates formed from the abundant elements O, Si, Mg and Fe. Out of these four elements silicate grains form as silica tetrahedras (SiO_4) combined with Mg^{2+} or Fe^{2+} cations. In the crystalline lat-

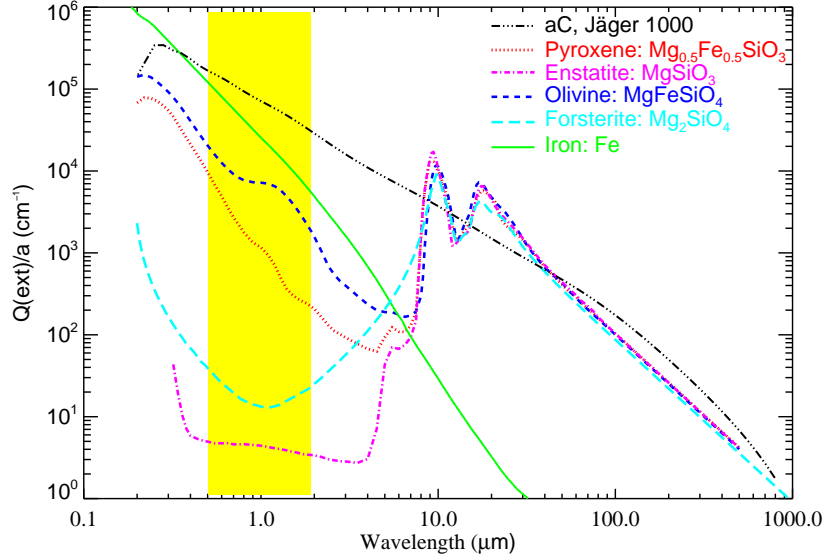


Figure 2. Calculated extinction efficiency, Q_{ext} , over particle radius, a , in the Rayleigh-limit for different types of silicates (Dorschner et al. 1995; Jäger et al. 2003). For comparison pure iron and amorphous carbon (cel 1000) from Jäger et al. (1998) are shown. Notice that the different silicates have extinction efficiencies which are several orders of magnitude below that of amorphous carbon in the wavelength region of maximum flux for typical AGB photospheres (indicated by the shaded area). Iron rich silicates have stronger absorption around $1\mu\text{m}$ than iron poor silicates.

tice structures it is possible for the tetrahedras to share their oxygen atoms with other tetrahedras and thereby form many different types of silicates (Molster & Kemper 2005), which are described by

$$\text{Mg}_{2x}\text{Fe}_{2(1-x)}\text{SiO}_4 \text{ with } x \in [0, 1]$$

$$x = 1 \rightarrow \text{forsterite}, x = 0 \rightarrow \text{fayalite}, 0 < x < 1 \rightarrow \text{olivine}.$$

$$\text{Mg}_x\text{Fe}_{(1-x)}\text{SiO}_3 \text{ with } x \in [0, 1]$$

$$x = 1 \rightarrow \text{enstatite}, x = 0 \rightarrow \text{ferrosilite}, 0 < x < 1 \rightarrow \text{pyroxene}.$$

The optical properties of these silicates all have resonances around $10\text{--}20\mu\text{m}$, due to the Si-O stretching and the O-Si-O bending mode arising from the silica-tetrahedras. Alignment of the tetrahedras may cause sharp peaked resonances, whereas amorphous silicates will show a broad feature which can be seen as a blend of such sharp resonances. The extinction efficiency of different silicates can be seen in Fig. 2. For comparison the amorphous carbon data from Jäger et al. (1998) (presented in Fig. 1) and iron from Palik (1985) are also shown. What characterises silicate grains is the lack of strong absorption in the range where AGB stars have most of their flux.

The slope of the dust absorption efficiency around the maximum flux of the AGB photosphere influences the dust grain temperature. The steeper the slope the higher the dust grain temperature will be. A high dust grain temperature

will prohibit dust formation in the stellar atmosphere (see the contributions from Höfner and Woitke in these proceedings for more details). The iron rich silicate grains are therefore prevented from forming and the iron poor silicate grains do not have high enough opacity to drive the wind. These grain properties of silicate grains have currently turned the mass loss mechanism of oxygen-rich AGB stars into a bit of a puzzle.

6. Summary

Galaxies are constantly enriched by dust produced in the cool stellar atmospheres of AGB stars. Small amounts of these grains have been incorporated into presolar grains which can be extracted from meteorites. Results from isotopic studies of these grains have made it possible to trace the grains' to specific stellar sources. A major fraction of these grains originate from AGB stars at different phases in their AGB evolution. Given the precision of the laboratory isotopic analyses, which by far exceeds whatever can be hoped for in remote analyses, it is possible to obtain detailed information regarding nucleosynthesis and mixing in the parent stars as well as important hints towards obtaining a better understanding of the galactic chemical evolution.

For interpretation of observations the single most important parameter for dust are the extinction properties of a specific species. These are often measured in the laboratory on synthetically produced cosmic dust analogues.

Acknowledgments. The author would like to thank Susanne Höfner, Uffe Gråe Jørgensen and Peter Woitke for fruitful discussions and Franz Kerschbaum for endless patience. The Dark Cosmology Centre is funded by the Danish National Research Foundation.

References

- Alexander, C. M. O'D., 1997, in: T. J. Bernatowicz, & E. K. Zinner (eds.), *Astrophysical implications of the laboratory study of presolar materials*, AIP Conf. Proc. 402 (Woodbury: AIP), p. 567
- Amari S., Anders E., Virag A., Zinner E.K., 1990, Nat 345, 238
- Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta 53, 197
- Andersen A. C., Höfner S., Gautschy-Loidl R., 2003, A&A 400, 981
- Bernatowicz T. J., Fraundorf G., Tang M., Anders E., Wopenka B., Zinner E. K., Fraundorf P., 1987, Nat 330, 728
- Bernatowicz T. J., Amari S., Zinner E. K., Lewis R. S., 1991, ApJ 373, L73
- Bernatowicz T. J., Akande O. W., Croat T. K., Cowsik R., 2005, ApJ 631, 988
- Bohren C. F., Huffman D. R., 1983, Absorption and Scattering of Light by Small Particles, John Wiley & Sons, New York
- Campbell M. F., Elias J. H., Gezari D. Y., et al., 1976, ApJ 208, 396
- Croat T.K., Stadermann F.J., Bernatowicz T.J. 2005, ApJ 631, 976
- Debye P., 1909, Ann. Phys. 30, 57
- Dorschner J., Begemann B., Henning Th., Jäger C., Mutschke H., 1995, A&A 300, 503
- Friedemann C., 1969a, Physica 41, 139
- Friedemann C., 1969b, Astron. Nach. 291, 177
- Gilman R. C., 1969, ApJ 155, L185
- Gürtler J., Kömpe C., Henning Th., 1996, A&A 305, 878
- Hackwell J. A., 1972, A&A 21, 239

- Henning Th., Il'In V.B., Krivova N.A., Michel B. & Voshchinnikov N.V., 1999, A&AS136, 405
- Heras, A. & Hony, S., 2005, A&A 439, 171
- Hoppe P., Ott U., 2007, in High-lights of Astronomy XXIV, ed. K.A. van der Karel, in press
- Hoppe P., Zinner E., 2000, J. Geophys. Res. A105, 10371
- Hoppe P., Ott U., Lugmair G.W., 2004, New Astron. Revs. 48, 171
- Huffman D.R., 1988, Methods and difficulties in laboratory studies of cosmic dust analogues. In: E. Bussoletti, C. Fusco, G. Longo (eds.) Experiments on Cosmic Dust Analogues, Kluwer Academic Publishers, 25
- Huss G., Lewis R.S., 1995, Geochim. Cosmochim. Acta 59, 115
- Huss G.R., Hutcheon I.C., Wasserburg G.J., 1997, Geochim. Cosmochim. Acta 61, 5117
- Hutcheon I.D., Huss G.R., Fahey A.J., Wasserburg G.J., 1994, ApJ 425, L97
- Jäger C., Mutschke H., Henning Th., 1998, A&A 332, 291
- Jäger C., Fabian D., Schrempel F., Dorschner J., Henning Th., Wesch W., 2003, A&A 401, 57
- Kemper F., Waters L.B.F.M., de Koter A., Tielens A.G.G.M., 2001, A&A 369, 132
- Kragh H., 1991, Appl. Opt. 30, 4688
- Lewis R.S., Tang M., Wacker J.F., Anders E., Steel E., 1987, Nat 326, 160
- Maron N., 1990, Ap&SS 172, 21
- Martin P.G., Rogers C., 1987, ApJ 322, 374
- Mie G., 1908, Ann. Physik 25, 376
- Molster F.J., Waters L.B.F.M., Tielens A.G.G.M., Barlow M.J., 2002, A&A 382, 184
- Molster F., Kemper C., 2005, Space Science Reviews 119, 3
- Mutschke H., Andersen A.C., Clément D., Henning Th., Peiter G., 1999, A&A 345, 187
- Nittler L.R., Alexander C.M.O'D., Gao X., Walker R.M., Zinner E.K., 1994, Nat 370, 443
- Nittler L.R., Hoppe P., Alexander C.M.O'D., Amari S., Eberhardt P., Gao X., Lewis R.S., Strebel R., Walker R.M., Zinner E.K., 1995, ApJ 453, L25
- Nittler L.R., 2003, Earth Planet. Sci. Lett. 209, 259
- Nuth J.A. III, Wilkinson G.M., Johnson N.M., Dwyer M., 2006, ApJ 644, 1164
- Ossenkopf V., Henning Th., Mathis J.S., 1992, A&A 261, 567
- Ott U., 1993, Nat 364, 25
- Palik E.D., 1985, *Handbook of optical constants of Solids*, Academic Press Inc. (Orlando)
- Papoular R., Cauchetier M., Begin S., LeCaer G., 1998, A&A 329, 1035
- Preibisch Th., Ossenkopf V., Yorke H.W., Henning Th., 1993, A&A 279, 577
- Rayleigh, Lord, 1871, Philos. Mag. 41, 107; (reprinted in Scientific Papers by Lord Rayleigh, Vol I: 1869-1881, No. 8, Dover, New Your, 1964.
- Rouleau F., Martin P.G., 1991, ApJ 377, 526
- Russell S.S., Lee M.R., Arden J.W., Pillinger C.T., 1995, Meteoritics 30, 399
- Sopka R.J., Hildebrand R.H., Jaffe D.T. et al., 1985, ApJ 294, 242
- Sylvester R.J., Kemper F., Barlow M.J., de Jong T., Waters L.B.F.M., Tielens A.G.G.M., Omont A., 1999, A&A 352, 587
- Treffers R., Cohen M., 1974, ApJ 188, 545
- Wasserburg, G. J., Boothroyd, A. I., Sackmann, I.-J., 1995, ApJ 447, L37
- Waters L.B.F.M. et al., 1996, A&A 315, L361
- Waters L.B.F.M., Cami J., de Jong T., Molster F.J., van Loon J.T., Bouwman J., de Koter A., Waelkens C., Van Winckel H., Morris P.W., 1998, Nature 391, 868
- Zinner E.K., 1998, Annu. Rev. Earth Planet. Sci. 26, 147
- Zinner, E.K., 2004, in: K. K. Turekian, H. D. Holland, A. M. Davis (Eds.), *Treatise in Geochemistry 1*, Elsevier, Oxford and San Diego, p. 17
- Zubko V.G., Menella V., Colangeli L., Bussoletti E., 1996, MNRAS 282, 1321.