LABORATORY INVESTIGATIONS AND OPTICAL PROPERTIES OF GRAINS

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ABSTRACT. A survey on different techniques of scattering measurements is given. Typical results are presented. Efficiency and limits of theoretical methods available are shortly summarized. Special emphasis is given to the demands on future laboratory experiments needed for the interpretation of polarization and colour effects produced by interplanetary and cometary dust.

1. INTRODUCTION

Light scattering problems can be roughly divided into two groups: In the case of the "D i r e c t S c a t t e r i n g P r o b l e m" the physical properties of the particles are known and their light scattering properties are wanted. A typical example for the application of the findings is the radiation transfer in the earth's atmosphere. But such results are also necessary for the solution of the "I n v e r s e S c a t t e r i n g P r o b l e m". In this case the access to the particles in question is difficult and thus the light scattering signature is a very important if not the only source of information concerning their physical properties. Typical examples for this case are interstellar, interplanetary, and cometary dust and dust in planetary atmospheres. According to the broad field of applications numerous publications deal with the problem to derive scattering functions theoretically or experimentally.

2. FORMALISM

Generally a scattering process may be described proceeding from a linear transformation (see van de Hulst, 1957).

$$\begin{pmatrix} I_{s1} \\ I_{s2} \\ U_s \\ V_s \end{pmatrix} = \frac{\lambda^2}{4\pi^2 r^2} \begin{pmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{pmatrix} \cdot \begin{pmatrix} I_{o1} \\ I_{o2} \\ U_o \\ V_o \end{pmatrix}$$

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Index 0 characterizes the Stokes vector of the incident radiation, index s that one of the scattered radiation. λ is the wavelength; r is the distance between scattering particle and observer. The indices 1 and 2 characterize the direction of the electric vector perpendicular and parallel to the scattering plane, respectively. The significance of all elements of the Mueller-matrix has been investigated by Perry et al., 1978 and Bottiger et al., 1980. Their measurements indicate, that for most applications the elements A_{11}, A_{12}, A_{21}, and A_{22} are dominant. They determine I_{s1} and I_{s2} of the Stokes-vector of the scattered radiation if the incident radiation is unpolarized or either polarized perpendicular or parallel to the scattering plane. It should be mentioned, however, that for special applications the evaluation of elliptical polarization can be very powerful. In this case other matrix elements also play a significant role, for instance A_{34} for the investigation of biological cells (Bickel and Stafford, 1980).

The elements $A_{12} \equiv A_{21}$ (they are identical if certain symmetry conditions are satisfied, see van de Hulst, 1957) characterize the cross-polarizing effect of particles; they are zero for single scattering spheres, but can reach the same order of magnitude than A_{11} and A_{22}in the case of large irregular transparent particles.

Proceeding from the matrix elements mentioned above, the total scattering function $i = A_{11} + A_{22} + 2\ A_{12}$ and the degree of linear polarization

$$P = \frac{A_{11} - A_{22}}{i}$$

can be defined. These quantitaties illustrate the scattering properties in the examples given at the end of this contribution.

3. METHODS TO DETERMINE SCATTERING PROPERTIES

3.1 Theoretical Methods and their Limits

Despite continuous improvement of computers the theoretical methods to determine scattering functions are still restricted concerning shape, refractive index, size and/or orientation. Exact solutions, comparable to Mie-theory for spheres, exist for infinite cylinders (Rayleigh, 1881; Lind and Greenberg, 1966) and for spheroids (Asano and Yamamoto, 1975, Schaefer, 1980). Other methods are restricted to certain sizes (particles very small compared to the wavelength: Rayleigh, 1881), special refractive indices (Debye, 1915) or only minor deviations from spherical shape ("Point Matching": Oguchi, 1973; Bates, 1975; Yeh and Mei, 1980. "Perturbation Method" : Yeh, 1964; Erma, 1969). The "T-Matrix Method" (Waterman, 1971; Barber and Yeh, 1975) as well as the theory of Purcell and Pennypacker (1973) reach their limits, if larger particles and different orientations are to be considered, due to the immense demand on computing time. Other methods are not generally applicable because they are based one simplifying assumptions (Gustafson, 1980; Wolff, 1975, 1981; Mukai, 1980; Lumme and Bowell, 1981; Schiffer and Thielheim, 1982, 1984 this volume;

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Chiappetta, 1980; Perrin and Lamy, this volume). The same holds for some semiempirical methods (e.g. Chylek et al., 1976; Pollack and Cuzzi, 1980; Giese et al., 1978). Nevertheless, the agreement between observed scattering features and the results obtained by the theoretical methods mentioned above can be surprisingly good. But because of the restrictions also mentioned laboratory measurements are still necessary. An important application of them is to determinate the range of validity of theoretical methods.

3.2 Experimental Methods

Depending on the specific application different experimental methods can be applied in order to obtain scattering results. Fig. 1 gives a schematic overview.

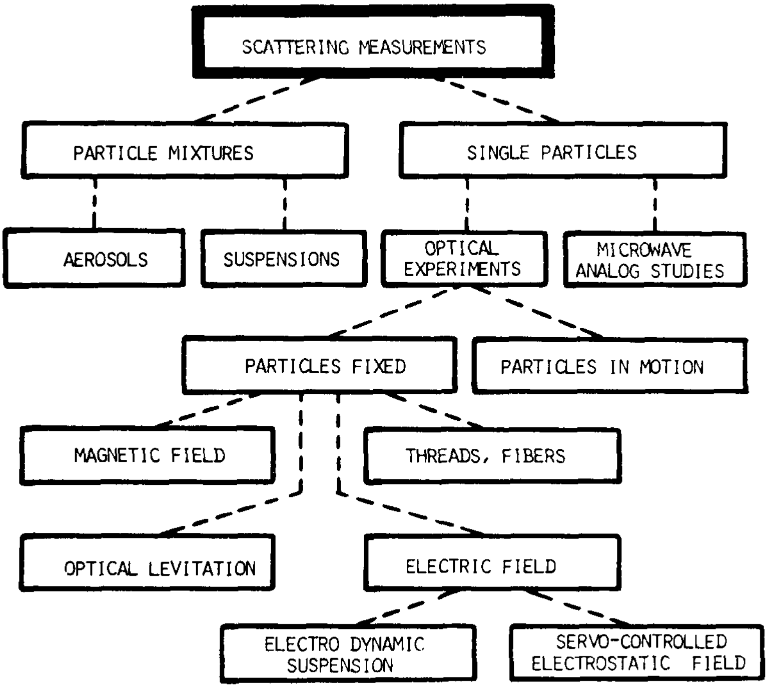

Figure 1. Experimental Methods for Scattering Measurements.

The measurements can be roughly divided into two groups, considering single particles or ensembles of particles, respectively. The latter case is optimized for rapid overall in-situ analysis of particles, where details of single particles are of minor interest. Typical examples are the measurements of Holland and Gagne (1970) and Perry et al. (1978).

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The experimental effort becomes by far higher for single particle measurements. This holds in particular for microwave analog studies as initiated by Greenberg et al., 1961 and Giese and Siedentopf, 1962. They take advantage of the fact, that the electromagnetic laws are valid over a wide range of wavelengths, i.e. 4 orders of magnitude between the optical and the microwave region. Analog conditions in both regions are provided for the same ratio of particle size to wavelength and by choice of materials with the same refractive index. Scattering results for mono- and polydisperse mixtures must be composed of data for different orientations and sizes, which can become quite laborious. The advantage of microwave analog studies is, that orientation, size, shape, structure, and refractive index of the particles can be varied systematically and exactly. Microwave Laboratories for applications concerning cosmic dust exist at the "Space Astronomy Laboratory", Gainesville, Florida and at "Bereich extraterrestrische Physik", Ruhr-Universität Bochum. At Gainesville the priority has been given to measurements of dielectric regular nonspherical particles (cylinders, spheroids: see Schuerman et al., 1981), including extinction and radiation pressure efficiency. At Bochum, highly irregular structures of more or less absorbing particles have been a special point of interest (Zerull et al., 1980).

For the most part measurements of single particles are carried out directly in the optical region. The measurement and evaluation of the light flashes of moving particles is a typical technique for in-situ experiments; systematic studies, however, should be performed having the particles fixed. In this case the measurement of the physical and chemical properties (microscope, SEM, mass spectrometer etc.) and conclusions concerning their connection with observed scattering features become possible. Fixing of particles can be obtained using threads (for example spider threads: Saunders, 1980). In order to obtain reliable results the application of this principle should be restricted to particles which are sufficiently large compared with the thread diameter.

The other suspension methods work without contacting the particle. Adequate to balance gravity are radiation pressure and magnetic or electric forces. Restrictions concerning the particle material must be observed in the case of magnetic (Beams, 1954) and optical levitation (Ashkin and Dziedzic, 1971, 1980). The latter requires low absorption to avoid evaporation of the particles in the strong laser beam. The advantage of optical levitation is, that radiation pressure automatically centers the particle within the laser beam.

Charged particles can be suspended by electric forces. A servo-controlled "Millikan-field" (Electrostatic suspension: Wyatt and Phillips, 1972; Bottiger et al., 1980) can be used for this purpose as well as a superposition of AC- and DC-fields ("Electrodyamic suspension": Wuerker et al., 1959; Straubel, 1960; Weiss-Wrana, 1983, Weiss-Wrana et al., this volume).

4. RESULTS AND FUTURE NEEDS

The extent of this contribution does not allow to give a complete overview of all laboratory measurements available. Instead of that it may, however, be tried to give a rough idea about the relations beween observed scattering features and physical properties of the particles, illustrated by a few examples.

4.1 Relations between Scattering Features and Particle Properties

Table I illustrates the connection between particle properties (size, material, outer shape and inner structure) and typical features of measured quantities (intensity, linear polarization, colour, cross polarisation).

TABLE I

Connection between Particle Properties and Scattering Features.

QUANTITY MEASURED	TYPICAL FEATURES	CONNECTION WITH PARTICLE PROPERTIES
INTENSITY	ENHANCEMENT OF FORWARD SCATTERING	SIZE
	ENHANCEMENT OF BACKSCATTERING	SHAPE MATERIAL
LINEAR POLARIZATION	LOCATION AND MAGNITUDE OF POSITIVE MAXIMUM LOCATION OF NEUTRAL POINT MAGNITUDE OF NEGATIVE BRANCH	MATERIAL SHAPE STRUCTURE SIZE
COLOUR EFFECTS	CHANGE OF FEATURES ABOVE WITH COLOUR	MATERIAL STRUCTURE SIZE
CROSS POLARIZATION	MAGNITUDE OF CROSS-POLARIZING ELEMENTS OF MUELLER-MATRIX	MATERIAL SHAPE SIZE

Concerning intensity and linear polarization, the information available is quite comprehensive, regarding laboratory measurements and observations, as well. Some typical examples of laboratory measurements are shown in the next section.

All features observed in the scattering pattern can vary with wavelength. The following reasons may be responsible for such colour effects:

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- The index of refraction varies with wavelength.
- The particle size is in the range, where the scattering efficiency strongly depends on the ratio of size and wavelength.
- Microstructure of the particles, i.e. single constituents may be in the size range mentioned above, and/or the distance between the constituents, relative to the wavelength, varies.

The reproduction of the correct colour dependence is a powerful tool to check the validity of different models of the zodiacal light cloud and cometary dust, as well. Unfortunately some basic requirements for full use of this criterion are still lacking such as a comprehensive knowledge and understanding of the colour effects produced by different types of particles. Promising experiments to solve this problem, however, are on the way (see Weiss-Wrana et al., this volume). Available observations are also somewhat ambiguous, in particular concerning the colour dependence of polarization. Comparing different results for comets the situation is almost confusing (Michalsky, 1981; Kneissel et al., 1983; Doose et al., 1974; Kiselev et al., 1978; see also Weiss-Wrana et al., this volume). But there are also different statements concerning the colour dependence of the polarization of the Zodiacal Light (Weinberg and Sparrow, 1978; Leinert et al., 1981). Space experiments in the near future will problably help to remove ambiguities and allow, together with appropriate laboratory results, to take full advantage of the significance of colour effects.

Another scattering effect sensitive to particle properties is cross-polarization. It can easily be measured in the laboratory illuminating the particles with a linearly polarized beam. If the incident light is unpolarized, as in the case of the sun, cross polarization is still present but cannot be separately measured. This reduces the value of that criterion at the moment. It is mentioned nevertheless as it may gain importance by chance of future space experiments, for instance during a comet rendezvous mission, where dust particles can be illuminated by artificial light sources.

4.2 Typical Scattering Measurements

This contribution may be concluded by presenting the results of 6 typical scattering measurements in order to illustrate the effects of size, shape, material, and structure of particles, as generally mentioned in the previous section. In each figure results of microwave analog studies (left hand side, Zerull et al. 1977, 1980) are contrasted to laser scattering experiments (right hand side, Weiss, 1981; Weiss-Wrana, 1983). All results are compared to Mie-calculations or Fresnel-reflection curves of equivalent spheres; the base of comparison are the volume (microwave measurements) or the mean geometric cross section (laser results), respectively. Referred to the optical region, the microwave particles simulate particles of several microns, whereas the particles measured with the laser equipment are approximately one order of magnitude larger.

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Fig. 2 illustrates effects of increasing deviation from spherical shape. Rough spheres (roughness ~ 1/10 wavelength) do not scatter significantly different from smooth spheres (left diagram). Backscattering enhancement, in particular, is fully preserved. This is obviously not the case for the deformated glass sphere (right diagram).

Fig. 3 illustrates, again for dielectric material, how stronger deviations from spherical shape affect the scattering diagram. Basically the same effects occur as already observed in the case of a deformated glass sphere: Less polarization, increased intensity at medium scattering angles, no enhanced backscattering.

Fig. 4 illustrates the typical scattering properties of highly irregular absorbing particles. Lower polarization with the maximum closer to 90° and intensity continuously increasing toward backscattering are the dominant differences with respect to spheres.

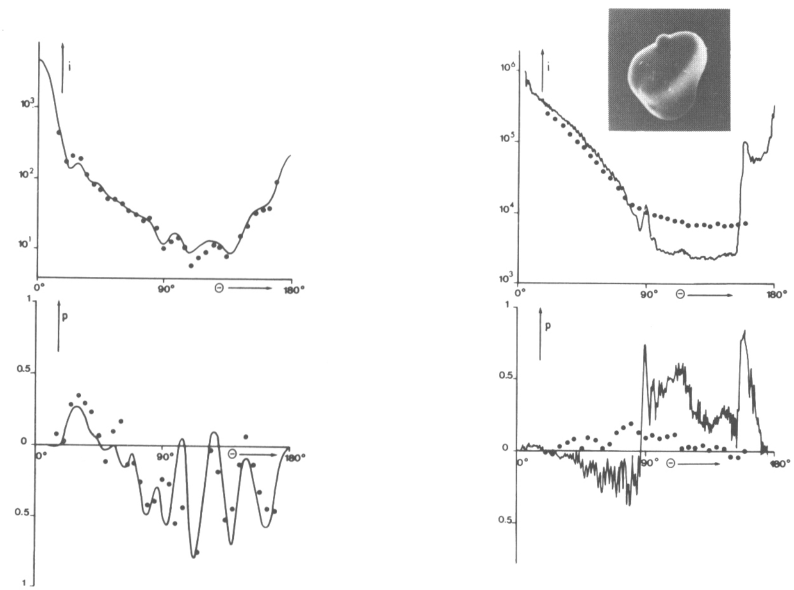

Figure 2. ····· Rough Spheres; ——— Smooth Spheres; $m = 1.57-0.006i$; $5.3 \leq \alpha \leq 14$ ····· Deformed Glass Sphere; ——— Ideal Sphere (Mie); $m = 1.51$ $\alpha = 320$

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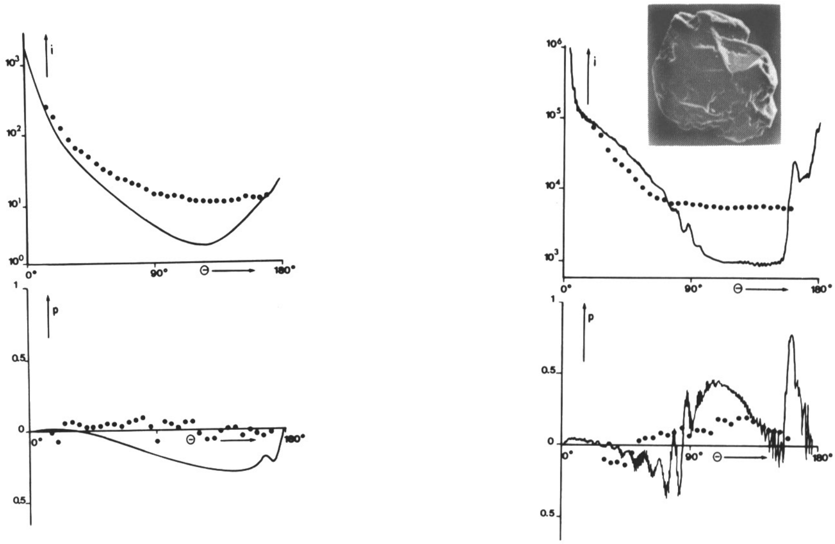

Figure 3. ····· Nonspherical Particles ····· Quartz Particle

——— Spheres (Mie) ——— Sphere (Mie)

m = { 1.5 -0.005i ; 1.57 -0.006i ; 1.70 -0.015i } $1.9 \leq \alpha \leq 17.8$ m = 1.54 α = 150

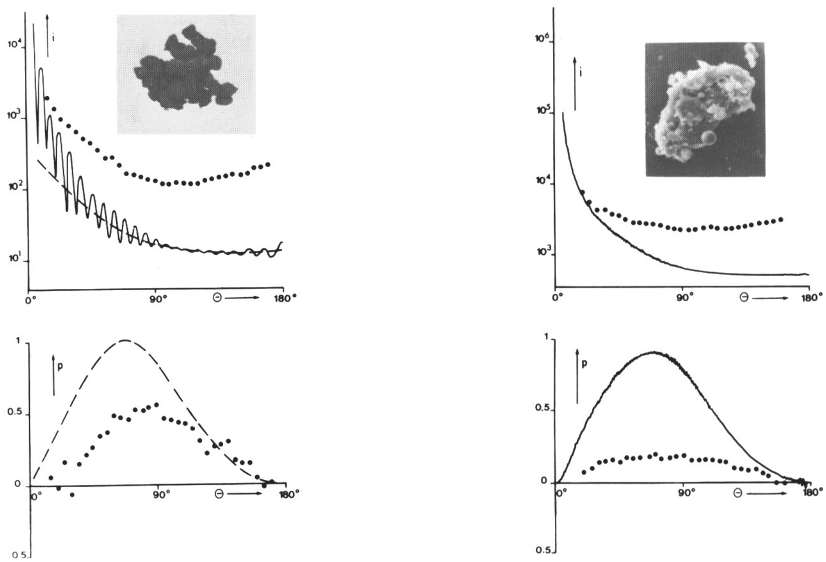

Figure 4. ····· Fluffy Particle ····· Flying Ash Particle

——— Sphere (Mie) ——— Sphere (Mie)

----- Sphere (Fresnel Refl.)   m = 1.55-0.01i α = 190

m = 1.45-0.05i α = 27

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6. DISCUSSION

Koutchmy: I wonder if there exist not any attempts to compute theoretically and also to measure the V-Stokes parameter (circular polarization) and if not, why?

Answer: The elements of the Mueller-matrix relevant for the determination of the parameter V of the Stokes vector of the scattered radiation have been measured by Bottiger et al., 1980, Thompson et al., 1980, Perry et al., 1978, and Bickel and Stafford, 1980.

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