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Backscattering of light from solar system ices and regoliths

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Academic Dissertation

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"Measure what is measurable, and make measurable what is not so."
Galileo Galilei (1564-1642)

Abstract

The study of the surface materials of small solar system objects can provide us with information on their origin and evolution as well as the early stages of the entire solar system. One way to study the surface texture of these objects is to investigate the directional properties of the light scattered from them. The method also has applications in remote sensing of terrestrial surfaces.

This thesis aims to improve the methods of solar system remote sensing by the study of the photometric and polarimetric properties of light scattered as a function of phase angle, especially near the direction of the source. The current methods of phase curve interpretation are evaluated and restrictions of the whole approach are discussed. It is pointed out that a conclusive phase curve interpretation requires a stronger empirical approach. This includes systematic laboratory measurements and empirical modelling of data. A novel laboratory device is constructed and results on backscattering are presented for ices and regolith-type samples. Phenomena similar to those found for many solar system ices and regoliths are observed with laboratory samples and terrestrial ices. These results are an important addition to the present supply of experimental data. They also are a starting point to a collection of a whole library of measurements, which is needed for extensive conclusions on surface properties. Methods of empirical modelling are presented and applied to the phase curves of icy satellites, asteroids, and laboratory samples. Empirical modelling is a powerful tool in the comparative classification of phase curve properties such as the amplitude and width of the backscattering intensity peak.

The results presented in this thesis provide new prospects for more conclusive interpretation of phase curves. The main focus of the study has thus far been laid on modelling, and only diverse information has been derived from phase curves. The experimental approach is essential in improving the general view on the opposition effect and testing and applying the physical models. A reliable means for retrieving surface properties from phase curves must be established to make their study a powerful remote sensing tool.

Preface

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Contents

1 Introduction: the opposition effect

The light scattered from the surfaces of solar system objects brings information on the nature of their surfaces, which are studied to improve our knowledge on the origin and evolution of minor planets and of the entire solar system. The phase curve study of the small solar system objects aims to a better understanding of their surface texture, and is closely related to the backscattering study of terrestrial regolith materials and laboratory samples. The variations in intensity or polarization properties as a function of the phase angle (the angle defined by light source, target, and observer), i.e., the phase curves (see Fig. 1) are known to be characteristic of the surface microstructure. Therefore, the phase curves provide a basis for remote sensing.

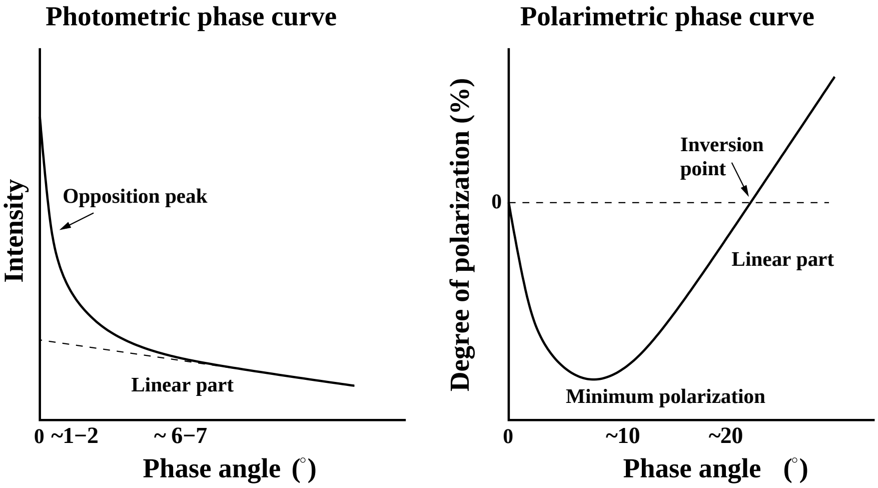

Figure 1: Schematic drawings of typical phase curves.

The brightness increase with decreasing solar phase angle (i.e. when the target approaches the astronomical opposition) is exhibited by the majority of atmosphereless objects in the solar system and is generally called the opposition effect. At small phase angles, the degree of linear polarization is negative. The sharp surge of the negative linear polarization towards small values close to the opposition is sometimes called the polarimetric opposition effect.

1.1 Photometric observations

Since the discovery of a brightness peak in the phase curve of Saturn's rings by Seeliger (1887), numerous works have been published on both photometric and polarimetric opposition effect. The history of the opposition effect study, as well as numerous observations, have been extensively reviewed in several earlier works

(Hapke 1993, Muinonen 1994, Piironen 1998, Shkuratov *et al.* 2002 and refs. therein, Muinonen *et al.* 2002a, see also paper I).

The phase curve study of the Moon ranges from telescopic observations to spacecraft data. Both whole-disk and disk-resolved photometry of different terrains are available, and the properties of different terrains have been compared (Helfenstein & Veverka 1987 and refs. therein, Buratti *et al.* 1996, see also Shkuratov *et al.* 1999 for a review). Unlike other extraterrestrial objects, lunar soil has been studied in the laboratory using the soil samples brought by Apollo missions (Hapke *et al.* 1993). Other than lunar rocks, meteorites are the only samples from space, but they cannot be that directly related to any single object. The main emphasis in many studies of lunar photometry has been in testing the available scattering models, which have also provided basis for the interpretation of the data in terms of the model parameters. Further disk-resolved images of the lunar surface, also at small phase angles, are expected to be provided by the forthcoming SMART-1 mission to the Moon, especially its AMIE microcamera (Muinonen *et al.* 2002a).

Several space missions have provided disk-resolved data and high resolution imaging of the planets and their satellites and rings. The spacecraft have also reached phase angles not observable from Earth, and the data has been used to complement the telescopic phase curves. The opposition effect of Martian regions has been studied from e.g. Phobos-2 data (Shkuratov *et al.* 1998), to map the spectral dependence of the amplitude of the brightness peak. Phase curves for icy Jovian, Saturnian, and Uranian satellites have been obtained from space missions such as the two Voyagers and Galileo mission to Jupiter, and the results have often been analyzed together with ground-based telescopic data. The missions have provided more accurate information on the surfaces of these objects (Buratti & Veverka,1983, 1984, Buratti *et al.* 1990, see also paper I for more references), and the opposition peaks of e.g. different terrains of Europa could be compared (Helfenstein *et al.* 1998). Recently, photometry of Mercury from SOHO solar spacecraft has been obtained (Mallama *et al.* 2002). Mercury's phase curve could be determined more accurately, and used in determining e.g. the geometric albedo.[1] Among the latest results are also the Hubble Space Telescope phase curves for Saturn's rings (Poulet *et al.* 2002), that enabled an analysis of grain roughness. Photometry of the rings and satellites of Uranus have also been obtained from the Hubble Space Telescope at phase angles down to 0.3°, indicating that these objects were brighter than earlier observed (Karkoschka 2001). Ground-based opposition photometry has also become available for the Neptunian satellite Nereid (Schaefer & Tourtellotte 2001) that is speculated to be actually a

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[1] **Geometric albedo:** the ratio of the brightness at 0° to that from a perfectly reflecting disk of the same size.

captured Kuiper Belt object (KBO). The Kuiper Belt objects are usually observed only at very small phase angles, preventing any effective study of the opposition effect. The first phase curve measurement for KBO's has recently presented by Schaefer & Rabinowitz (2002).

The Asteroid Photometric Catalogue (Lagerkvist *et al.* 2001) contains most of the available lightcurves of asteroids. The phase curves have been determined from lightcurve observations in varying ways, using e.g. maxima or minima, or fitting the mean intensity by using e.g. Fourier analysis (Harris *et al.* 1989). The variable and complicated shapes of the asteroids introduce specific problems into the phase curve determination, such as corrections for the viewing and illumination geometries, and the shape of the object, which all have their effect on the shape of the phase curve (M. Kaasalainen *et al.* 2001). Even though many of these problems have not been addressed, the opposition effect has been widely studied for asteroids, in order to determine and compare their magnitudes and albedos (e.g. Harris *et al.* 1989, Lagerkvist & Magnusson 1990, Piironen 1998, Harris *et al.* 1999 and refs. therein, Belskaya & Shevchenko 2000, Shevchenko *et al.* 2002, see also refs. in paper V). Mottola *et al.* (1997) present results of one of the most extensive photometric and radiometric observing campaign for the near-Earth asteroid 6489 Golevka. The rotational and physical properties were determined from the combined observations (see also M. Kaasalainen *et al.* 2001).

Strong effort has been put into linking the photometric and polarimetric phase curve properties of asteroids with their taxonomic (spectral) classification (Capaccioni *et al.* 1989, Lupishko & Belskaya 1989, Clark *et al.* 2002). A notable reddening in the spectra of asteroids towards larger phase angles has been observed (Veverka *et al.* 2000 and refs. therein). Recently, disk-resolved spectral and photometric data at relatively small phase angles has been provided by the NEAR mission to 433 Eros (Veverka *et al.* 2000, Clark *et al.* 2002). A phase reddening was observed, and the opposition effect was studied as a function of wavelength.

1.2 Polarimetric observations

Polarimetric observations of satellites and asteroids are not as common as the brightness studies. Dollfus (1998) summarizes the previous works of lunar polarimetry and presents polarimetric analysis of several lunar regions and calibrations with laboratory measurements of terrestrial and lunar soil samples. Studies have also been published on the negative linear polarization of the Galilean satellites (Dollfus 1975, Rosenbush *et al.* and refs. therein), and Saturn's rings (Johnson *et al.* 1980, Mishchenko 1993, Dollfus 1978, where the earlier works on Saturn's ring polarimetry are summarized). These results have been used in the comparison of the polarimetric properties and in the development of polarization modelling. Combined with photometric and spectroscopic results, they have also been used in finding relations to surface structures. Reviews on asteroid polarimetry are given in e.g. Dollfus *et al.* (1979, 1989) and Muinonen *et al.* (2002c). Conclusions on the surface textures and compositions have been drawn: for example, the surface characteristics of M-type asteroids are suggested to resemble those of metallic powders and meteorites (Dollfus *et al.* 1979, Lupishko & Belskaya 1989). A few points of phase curve have also been observed to map the polarization characteristics of the cometary coma of P/Halley (Dollfus & Suchail 1987).

1.3 Modelling

The important features of the intensity peak near backscattering, concerning its interpretation, are the amplitude and the angular width of the peak (see Fig. 1). The slope of the linear part also characterizes the curve. The typical characteristics of the polarization phase curve are the amplitude and angular scale of the negative surge and the minimum degree of polarization. At larger phase angles the important parameters are the maximum polarization, the slope of the curve, and the so-called inversion angle, the point where the polarization changes back to positive. In this thesis, the main emphasis is laid on the backscattering parameters.

1.3.1 Models based on shadowing

Modelling of the opposition effect, started with interpretation of the brightness peak for Saturn's rings by Seeliger (1887), was for decades based on the shadowing mechanism. At opposition, i.e. at the backscattering direction, the surface particles are considered to hide their own shadows, resulting in increased brightness. Photometric equations were derived from radiative transfer theory, including corrections for shadowing (e.g. Irvine 1966), to be applied for the planetary surfaces. Reviews on the history and previous theoretical interpretation are given by e.g. Bowell *et al.* (1989), Mishchenko (1993), Muinonen (1994), Shkuratov *et al.* (2002), and Muinonen *et al.* (2002c). This Section reviews the models (and the parameters for surface characterization) with practical applications in the interpretation of opposition data.

Hapke's photometric model (1986) has been widely applied in the interpretation of lunar and planetary photometry as well as a great number of laboratory experiments (e.g. Buratti 1985, Bowell *et al.* 1989 and refs. therein, Verbiscer & Veverka 1990, Domingue *et al.* 1997 and refs. therein, Hartman & Domingue 1998). The model deals with numerous photometric parameters and other related quantities (summarized in e.g. Helfenstein & Veverka 1987, Clark *et al.* 2002), of which the following five are most often used in phase curve modelling:

- ϖ is the single scattering albedo (the efficiency of average particle to scatter and absorb light),
- h is the width of the opposition peak, which Hapke has related to soil structure (e.g. porosity and filling factor of the surface),
- $S(0)$ describes the amplitude of the peak,
- g is the asymmetry factor of the particle phase function (often expressed as the Henyey-Greenstein approximation, see e.g. Bowell *et al.* 1989)
- $\bar{\Theta}$ is the average topographic slope angle of surface roughness.

With the aid of these parameters, Hapke's model describes the opposition effect with the function (notation adopted from Piironen 1998):

$$B(\alpha, h, S(0)) = \frac{B_0}{1 + \frac{1}{h}\tan(\frac{\alpha}{2})} \tag{1}$$

where α is the phase angle and B_0 is the total magnitude of the opposition effect, given by

$$B_0 = \frac{S(0)}{\varpi}\frac{(1+g)^2}{(1-g)} \tag{2}$$

B_0 is not supposed to exceed unity for smooth opaque particles, but for rough composite particles (such as those of lunar terrains) this condition can be broken (e.g. Helfenstein & Veverka 1987). Helfenstein *et al.* 1997 have collected opposition surge amplitudes for a variety of solar system objects. A summary of five Hapke parameters for icy satellites is found in Verbiscer & Helfenstein (1998).

The radiative transfer model by Lumme & Bowell (1981a), and its application to asteroids (Lumme & Bowell 1981b) had originally four essential parameters (see also Karttunen & Bowell 1988): ϖ, the single scattering albedo, defining the total brightness and the proportion of multiple scattering, g, the asymmetry factor of the single-scattering phase function, such that highly negative g was related to strong backscatter, roughness ρ, the higher value of which was considered to increase the opposition effect, and the volume density D of the surface material: more porous material (smaller D) would increase the opposition peak. The two-parameter HG magnitude system for asteroids, adapted by IAU Commission in 1985, was developed from the Lumme & Bowell scattering model (Bowell *et al.* 1989). The V-band magnitude $H(\alpha)$ (at phase angle α) of an asteroid can be expressed as

$$H(\alpha) = H - 2.5\log[(1-G)\Phi_1(\alpha) + G\Phi_2(\alpha)] \tag{3}$$

where H is the absolute magnitude at $\alpha = 0$, G is the slope parameter, selected roughly to equal zero for steep phase curves (connected with low albedo objects), and unity for shallow phase curves (generally valid for high-albedo objects). The phase functions Φ_1 and Φ_2 are defined as

$$\Phi_i = \exp[-A_i(\tan \frac{1}{2}\alpha)^{B_i}], \qquad i = 1, 2 \tag{4}$$

where $A_1 = 3.33$, $A_2 = 1.87$, $B_1 = 0.63$, and $B_2 = 1.22$. Φ_1 and Φ_2 are related to surface roughness and porosity and the amount of multiple scattering in the regolith, respectively. The H, G-system has been applied to all asteroids for which orbits and magnitude observations are available (Bowell *et al.* 1989, Lagerkvist & Magnusson 1990). Verbiscer & Veverka (1995) provided the first quantitative translation between the H, G-system and Hapke's equations.

Both Hapke and Lumme & Bowell scattering models were based on the effects of shadowing (and surface roughness), which could not predict or reproduce the sharp opposition peaks (often termed as opposition spikes) observed for moderate and high albedo objects. These peaks were in fact in contradiction with the shadowing mechanism, which predicted that multiple scattering should mask the opposition effect at small phase angles (Helfenstein *et al.* 1997, Nelson *et al.* 1998).

The major difficulty in the application of both Hapke's and Lumme & Bowell's models in the interpretation of phase curves is the ambiguity of the fitting parameters: a unique set of parameters for a given phase curve can not be determined, even for moderately good quality data (e.g. Mallama *et al.* 2002). In fact, different parameters have very similar effects on the phase curves. Even though this problem has been pointed out by numerous authors (Helfenstein & Veverka 1987, Karttunen & Bowell 1989, Bowell *et al.* 1989, M. Kaasalainen *et al.* 2001, Mallama *et al.* 2002), these models are still applied to almost all new photometric data, and strong conclusions are drawn, usually justified by the fact that the fits look good either graphically or in terms of small RMS errors. However, even though all the data points lay on the graph of the function (which can be achieved for almost any function, given that the data is not too noisy) leading to a very small RMS, the problem with the ambiguity of the parameters would still remain. Neither does a small RMS prevent the parameters from being not only meaningless for the investigated surface, but also out of their physical range. This was the case for e.g. the Hapke parameter B_0 in Helfenstein *et al.* (1997) and Clark *et al.* (2002), so that further adjustments of the parameters had to be made. Moreover, in least squares fits of (mathematically) complicated functions, the initial values have to be relatively close to the solution, since the traditional fitting routines usually look for local minima. Therefore, even if the parameters looked physically realistic, they do not necessarily represent the surface material in question. In reverse, this means that using these models, the phase curves can be reproduced equally well (in terms of e.g. small RMS) using totally unrealistic parameters (M. Kaasalainen *et al.* 2001). One more point to consider is the lack of measurements and observations at and near zero phase, which would be essential in characterizing the opposition surge, especially its narrow components (Helfenstein *et al.* 1997). Many astronomical objects are eclipsed at zero phase. Asteroids can be observed at very small phase angles, which however is rare, for their orbits are usually not in the same plane as that of Earth's. For these reasons, observed values of e.g. parameter H of the H, G-system are mostly not available.

1.3.2 Coherent backscatter models

Coherent backscattering is a constructive interference effect between two rays travelling in multiply scattering medium in reversed paths. An intensity peak results in a narrow angular cone around the backscattering direction, caused by the equal phase of the waves. The effect was first related to the opposition effect of the Moon by Kuga & Ishimaru 1984. The phenomenon is also called weak localization of photons, especially in the field of condensed matter physics, where it is widely studied (see review by Eddowes *et al.* 1993, see also Totsuka & Tomita 1999 and refs. therein). Several solar system related studies have been published thereafter (Shkuratov 1989, Muinonen 1990, Mishchenko 1992). Recently, Hapke (2002) modified his light scattering model to include coherent backscattering. Two additional parameters, the amplitude and width of the coherent backscatter opposition peak were added.

Coherent backscattering as an explanation of the negative linear polarization was suggested by Shkuratov (1989) and Muinonen (1990). The effects of polarization have to be taken into account to compute more accurately the amplitude of the intensity peak and explain the sharp negative linear polarization effects, observed for e.g. icy Galilean satellites (Mishchenko & Dlugach, 1992, Rosenbush *et al.* 1997). Some works suggest the sharp surge in polarization at very small phase angles to be a separate effect from the more generally observed wider surge in negative polarization (Mishchenko 1993, Videen 2002). A greater number of observations would be essential for a better picture of these effects and the mechanisms involved. A vector approach was first presented by Ozrin (1992), and further applied by Mishchenko (1993) to compute the polarization opposition effect for Saturn's rings in a limited range of phase angles. The vector computation was used in Mishchenko *et al.* (2000) to present an vector solution for the polarization opposition effect in the full phase angle range. Numerical techniques have been put forward by e.g. Videen (2002). Muinonen (2002) presents a numerical Monte Carlo algorithm for multiple scattering including vector radiative transfer and coherent backscatter. The parameters varied in the study are the single scattering albedos and mean-free path parameters, the wavelength being held constant (Muinonen *et al.* 2002b). Black *et al.* (2001) fit the five-parameter vector coherent backscatter model by Peters (1992) to the radar reflectivities of icy Galilean satellites. Large uncertainties were found for parameter values and some maximum parameter values had to be fixed to reduce the ambiguity in the results. Shkuratov *et al.* (1999, 2002) use analytical approximations to interpret more easily the experimental data, e.g. Clementine observations of the lunar surface. The model describes the phase function with three parameters: k describes the shadow hiding effect, d describes the size of the scatterer, and L is the diffusion length of the internally scattered radiation field, which should increase with increasing albedo. This approximation has been applied comparatively for the Hubble Space Telescope observations of Saturn's rings phase curves by Poulet *et al.* (2002), where the effect of different parameters to both amplitude and width of the opposition peak is further discussed. Helfenstein *et al.* (1997) combine Hapke's photometric model with Mishchenko's description of coherent backscattering, and fit the results to the disk-integrated and disk-resolved observations of the Moon. The model contained finally eight parameters, but was reported to offer improvements compared to the classical shadow hiding models.

The models including coherent backscattering have succeeded better than the traditional scattering models in describing the sharp brightness increases and explaining the polarization opposition effect as a direct problem, thus contributing to a better understanding of the physics behind the effect. Their uses in the inverse problem, i.e. finding unique and realistic parameters from remote sensing data, has yet to be studied further. In the few fits presented this far, similar problems as in fitting the earlier photometric models have been encountered. Most of the coherent backscattering techniques that include polarization are numerical. Further simplifications are necessary to make them useful in the interpretation of data other than in comparative sense.

1.3.3 Empirical methods

Simple empirical functions have also been used in the qualitative interpretation of phase curves. Many of these are mathematical, with no connections to physical parameters. Empirical photometric functions such as Lambert and Minnaert laws are commonly used in e.g. albedo mapping (Verbiscer & Helfenstein 1998). Piironen (1994, 1998) applied an exponential formula to classify asteroid and snow data. The same function was later applied to Saturn's rings by Poulet *et al.* (2002), who found the computed amplitude of the opposition peak to grow with decreasing albedo of icy rings. A simple polynomial was also applied by Nelson *et al.* (2000) to extrapolate the maximums in zero phase for laboratory phase curves. Exponential functions and polynomials do not represent physical parameters, but provide a practical means to compare and classify the phase curve properties, often with less ambiguity than is encountered with the physical models described above.

1.4 Backscattering laboratory experiments

1.4.1 Experiments on intensity

Coherent backscattering is widely studied (both theoretically and experimentally) in the fields of optics and condensed matter physics. The effect was first discovered in laboratory by Kuga & Ishimaru (1984) followed by van Albada & Lagendijk (1985), and Wolf & Maret (1985). Several laboratory studies have been published thereafter (Yoon *et al.* 1993, Wiersma 1995, Eddowes *et al.* 1995 and refs. therein). Most of these studies have been carried out for spheres in liquid suspensions at very small phase angle ranges, typically up to some tenths of degrees (a few mrad below and above zero). Extremely narrow coherent backscattering patterns have been observed, from which the optical properties have been derived. The viewing geometries of astronomical objects hardly ever allow observations at such small phase angles, and the laboratory simulations have neither achieved the required angular resolution. This would be worthwhile for a further understanding of the effect and for testing the coherent backscattering models. In this angle range, notable shape variations of coherent peaks between different samples have been observed (see e.g. Wiersma *et al* 1995, Yoon *et al.* 1993). The coherent peaks have been used to monitor the particle distribution in colloidal suspensions (Ishii & Iwai 2000). The laboratory studies of coherent peaks have found important applications, such as optical coherence tomography, which can be used as a noncontact diagnostic tool (Scmitt *et al.* 1998 and refs. therein).

Opposition effect related astronomical backscattering studies appear in larger ranges of phase angle and resolution than in the field of condensed matter physics and optics. Reviews and references to previous laboratory simulations of the opposition effect of different solar system objects can be found in Helfenstein & Veverka (1987), Hapke (1993), Hapke *et al.* (1993), Muinonen (1994), Shkuratov *et al.* (2002). Examples of photometric laboratory measurements of the opposition effect and some related studies are summarized in Table 1. Various laboratory studies have been presented to simulate the opposition effect and to test the applicability of photometric models (Capaccioni *et al.* 1990 and refs. therein). In this section, the strongest interest is laid on the studies with systematic approach with respect to optical and surface parameters, which is important in a conclusive interpretation of the opposition effect. Furthermore, in many studies phase angles smaller than 1°-2° have not been achieved. This means that the part where coherent backscattering is supposed to take the major effect has been left out, and

Table 1: Related laboratory studies on the opposition effect.

Sample	Reference	Remarks/Results
Lunar soil (Apollo)	Hapke *et al.* 1993	Coherent Backscattering found to dominate OE
Single particles: Olivine and Allende	Muños *et al.* 2000	Neg. lin. polarization close to backscattering
Powdered meteorites:	Capaccioni *et al.* 1990, Lupishko & Belskaya 1989	Comparison to asteroids + classification
Terrestrial rocks, silicates, metals, (Sahara) sands	Capaccioni *et al.* 1990 Lupishko & Belskaya 1989 Muinonen *et al.*2002a (+ refs. therein)	Comparison to asteroids Lunar analog Grain size variation
Artificial (large) particles: glass, metal, resin	McGuire & Hapke 1995	Particle properties affect phase function
Powders: $BaSO_4$ MgO Al_2O_3 glass, metals, oxides etc.	Shkuratov *et al.* 1991 Nelson *et al.* 1998 Nelson *et al.* 1998, Nelson *et al.* 2000 Shkuratov *et al.* 2002	Stronger OE for more reflective samples Grain size variation Effects of particle size, compression etc.
Snow and ice	Piironen *et al.* 2000, this thesis	Impurity increases OE

shadowing has been studied at phase angles greater than 1°. Experiments at very small phase angles are crucial in reliable phase curve interpretation, regardless of the physical mechanism assumed to have the strongest effect.

Oetking (1966) compared the measured reflectivity curves of several samples of magnesium and aluminium oxide powders with varying grain size as well as basic rocks and other materials resembling the lunar surface to investigate the effect of grain size on the light scattering behaviour. He also carried out measurements for sugars to search for a brightness peak of clear and frosted sugar crystals. The results indicated that the grain size, shape and opacity of the material are strongly related to the shape and intensity of the opposition peak. However, Oetking's results are reported only down to 1°. Capaccioni *et al.* (1990) present grain size and packing density variations for pulverized rocks at phase angles down to 2°. They found the magnitude of the opposition effect to be partially dependent on the particle size, the peaks being weaker towards the finer sizes. They also found a stronger and sharper peak as the compaction of the finer grains was increased. This, however, they concluded to be possibly due to lack of data at phase angles less than 2°. They also presented a comparison of phase curves of meteorite powders with those of asteroids. Hapke *et al.* (1993) compared opposition peaks and linear and circular polarization ratios at phase angles down to 1° for Apollo lunar samples of different albedos. The aim of the experiment was primarily to provide evidence that the coherent backscattering is the principal cause of the opposition effect.

A beamsplitter-based instrument that could reach the zero phase angle was presented by Buratti *et al.* (1988). The effect of porosity on the opposition surge was investigated for two basalt samples. The fluffy regolith showed a larger opposition surge. They also demonstrated an opposition effect for a very bright barium sulfate sample. This instrument was improved by Nelson *et al.* (1998) to allow measurements of linear and circular polarization ratios, providing evidence that coherent backscattering is the major contributor in the opposition effect of regoliths. Moreover, they studied materials of different reflectances and found the more reflective materials to show stronger opposition peaks than the less reflective ones, which is also consistent with coherent backscatter theories. They replaced the beamsplitter by a mirror, which prevented the measurement in the exact zero phase. A similar mirror-based device was presented in Nelson *et al.* (2000) with a longer distance from the sample to the detector, to reach a minimum phase angle of 0.05°. Measurements of aluminium oxide abrasive powders of varying grain sizes were presented, and the size and width of the opposition peak turned out to be the largest when the particle size was very close to the wavelength of the incident light. The measurements by Nelson *et al.* (1998, 2000, 2002) are among the few ones with systematic variation of surface textural properties to search their effects on the phase curve at very small phase angles.

1.4.2 Polarization experiments

Extensive laboratory studies of the degree of linear polarization at small phase angles are extremely rare. The first laboratory measurements of negative linear polarization by Lyot (1929) have been used in many later studies (e.g. Mishchenko *et al.* 2000). Geake & Dollfus (1986) and Dollfus *et al.* (1989) present summaries of large-scale laboratory works carried out at the Meudon observatory as a continuation of Lyot's work: very small phase angles were not reached, but empirical relationships between polarization parameters, e.g. inversion angle and minimum polarization were found to be related to surface texture. The slope of the polarization phase curve is inversely related to the albedo of the sample, providing a method for surface albedo (and hence the average diameter) determination for remote objects. A classification of objects with surface grain roughness were presented. Mars, Mercury and Moon were characterized as fine grained and asteroids as coarse grained etc. Shortage of data near zero phase would perhaps call for new measurements to refine these conclusions. The polarimetry has been continued by Geake & Geake (1990) with measurements of fine alumina powders darkened in stages with carbon black. The polarization phase curves changed distinctively in shape with decreasing grain size down to subwavelength scales. Distinctive features such as the deep plunge in the minimum polarization for smaller grain sizes were found. Dollfus (1998) analyzed polarimetric data of ground meteorites, terrestrial samples, and lunar soil samples as a lunar polarimetry calibration. Polarization phase curves were presented for samples of different albedo and grain size. These studies did not include any results at very small phase either.

Lupishko & Belskaya (1988) present a variety of polarization phase curves for meteorite samples and a comparison with M-type asteroids. However, they did not report accurately the phase angle range of the measurements. From the polarization phase curves of basalt rocks, Shepard & Arvidson (1999) concluded these rocks to resemble C-type asteroids in the negative polarization behaviour. Laboratory work has also been carried out at Kharkov Observatory at phase angles 0.2° to 4° (Shkuratov *et al.* 2002), for regolith analogs. In those experiments, several effects of parameters such as particle size and wavelength were compared. Negative polarization was found to vary with the particle size, and the polarimetric and photometric opposition effects were observed to correlate. Recently, Ellis *et al.* (2002) have measured Mueller matrix elements[2] at backscattering geometry for dielectric and metallic surfaces. Mueller matrix elements at backscattering have been studied by e.g. Lewis *et al.* (1998) for roughened metal samples. The degree of linear polarization has not been discussed in these works. Scattering matrix elements have also been determined for single planetary particles such as phytoplankton and meteorite particles (Muños *et al.* 2000, Volten 2001), and compared with to e.g. comets, but excluding small phase angles.

1.4.3 Field experiments on snow and ice

Water ice is known to be present in the polar caps of Mars and in the outer planet icy satellites, as well as in rings and cometary comae (Grundy *et al.* 1999, Buratti 1999, Feldman *et al.* 2002). Recently, water ice has been detected in Centaurs and Kuiper belt objects (Luu *et al.* 2000). The circumstances (e.g. temperatures and pressures) in the surfaces of icy satellites are far different from those on the Earth, and ice phases other than hexagonal ice are present in the solar system (e.g. Grundy *et al.* 1999). Despite the fact, overall insight into the optical properties of snow and ice is useful in understanding the surface structures and optical properties of icy surfaces and ring particles.

The field study of the opposition effect of snow and ice provides a challenging geophysical application of phase curve investigation. Photometric experiments of terrestrial snow provide insights not only into the phase curve study of the icy solar system objects, but also into remote sensing of terrestrial snow and ices. Special

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[2] **Mueller matrix** relates the polarization state of scattered light to that of the incident light.

problems that are not present in the laboratory have to be considered, such as the restrictive effect of weather conditions and the rapid metamorphism of the target itself. Special focus has also to be put on target characterization.

There are several studies on physical properties of snow with respect to its spectra and reflectance. Especially the bidirectional reflectance function (BRDF[3]) for snow has been widely studied both experimentally and theoretically in the fields of glaciology and geophysics. Connections between grain size and BRDF are well understood (see Fily *et al.* 1998 for a review, Gerland *et al.* 1999 and refs. therein), but the measurements do not usually allow small phase angles. Therefore, backscattering is generally not discussed. Studies on albedo and its relation to physical properties are also common (Grenfell *et al.* 1994, Gerland *et al.* 1999, Winther *et al.* 1999). They are important in the remote sensing study of e.g. melting processes and snow cover thickness mapping.

Knowles Middleton & Mungall (1952) carried out goniometric measurements for six types of natural snow, and attempted to categorize snow surface types to point out the ones with highest luminances. This experiment is one of the first for natural snows, often referred to and analyzed thereafter (Veverka 1973, Verbiscer & Veverka 1990 and Domingue *et al.* 1997) to interpret the scattering properties of icy satellite surfaces. Most of the comparisons of the optical properties of terrestrial snows with those of icy satellites are still based on the measurements by Knowles Middleton and Mungall (1952). The results did not reach small phase angles, but it has been suggested that the backscattering signal of snow varies with snow type (Veverka 1973). Terrestrial snow was concluded to be mostly forward scattering (Verbiscer & Veverka 1990). In measurements reported by Shkuratov *et al.* (2002) strong peak was not observed for a snow sample at phase angles down to 0.2° either. An example of systematic comparison of laboratory and telescopic ice data is found in Quirico *et al.* (1999), where near-infrared spectra of Triton were analyzed together with those of ices of different composition. The spectra were used for comparison of spectral band positions and BRDF fitting.

The opposition effect for snow was discovered by Piironen (1994, see also Piironen *et al.* 2000 and paper VI) in his field measurements for visually pure and boron carbide contaminated snowballs. Miller *et al.* (1997) have reported an increase of intensity near the backscattering direction in their study of saline ices, but it has been interpreted to be possibly due to reflections from internal ice-air interfaces. Besides these, almost no studies exist on backscattering photometry for snow.

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[3] **Bidirectional reflectance distribution function** describes the ratio of radiance scattered into a given direction to the incident collimated power per unit area (see e.g. Hapke 1993).

1.5 Conclusions on the present study of the backscattering peak

The effects of individual parameters (such as packing density, grain size and shape, albedo etc.) on the opposition effect are not yet well understood, either by models or experiments (Bowell *et al.* 1989, Capaccioni *et al.* 1990). Generally, the opposition effect is predicted by shadowing functions to be small for high albedo materials. Coherent backscattering, on the contrary, has been interpreted to predict a peak increase due to multiple scattering (see Nelson *et al.* 1998, Poulet *et al.* 2002 and refs. therein). The effects of e.g. refractive indices and packing densities on the peak shape have also been discussed. The transport mean free path (related to porosity and particle size) has been concluded to be inversely proportional to the width of peak (Hapke *et al.* 1993, Mishchenko & Dlugach 1993, Shkuratov *et al.* 2002). Neither is the amplitude of the opposition effect completely understood, so empirical fits are encouraged (Hapke 2002, cf. Poulet *et al.* 2002). Mischcenko & Dlugach (1993) calculated that maximum effect should occur at particle sizes near wavelength. The effects of particle size and wavelength, however, have been shown by laboratory experiments to be much weaker than predicted (Nelson *et al.* 2000). The rounding of phase curves near zero for more absorbing materials, predicted by coherent backscattering models, has not been observed in the laboratory, but the peaks have been found to remain sharp (Nelson *et al.* 2002). The polarization characteristics such as the sharpness of the negative surge near zero have been found to be dependent on e.g. grain size and albedo, but the backscattering direction is not included in the studies.

Furthermore, no conclusive model exists to define which of the two mechanisms of scattering is dominant for a given surface (Helfenstein *et al.* 1997). A basis for experimental tests can be laid in investigating the ratios of linear and circular polarization.[4] According to shadowing, the ratios of circular and linear polarization should both decrease, whereas coherent backscattering should cause decrease in linear and increase in circular polarization ratios (Hapke *et al.* 1993, Nelson *et al.* 1998, 2000). The experiments of lunar surface have raised discussion both in favour of and against the coherent backscattering, based on wavelength dependencies (Buratti *et al.*1996) and polarization signatures, as discussed above. Laboratory studies are needed to map the combined effects of both mechanisms on the opposition effect.

The most severe problems in our understanding of the peak properties thus far are: 1) insufficient telescopic data (in terms of accuracy and coverage especially near zero phase), 2) lack of well organized laboratory studies: the studies presented thus far are for various special cases, while most of the systematic ones begin from e.g. 1° (e.g. in Hapke *et al.* 1993). This, however, does not prevent

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[4] **Polarization ratio:** the ratio of reflected intensity in the same polarization sense as incident to that in the opposite sense.

all the conclusions, but the very narrow peaks cannot be reached. 3) Constraints in modelling: ambiguity and no clear connection with experiments. Even if the accuracy of a dataset allows modelling, the reliability of the results – especially in retrieving the surface properties – is known to be limited (as previously explained).

The studies that would really extend our knowledge of the opposition effect would be controlled experiments that present data of good accuracy down to phase angles far less than 1° (cf. Buratti *et al.* 1988), and where the physical characteristics of the sample have been varied. As discussed, a few of these studies already exist, but a whole library of measurements is still to be acquired, both in photometry and polarimetry. This would improve our still somewhat scattered understanding especially on the effects of single parameters (and in further stages of study, of their combined effects). In addition to laboratory studies, there is a great need for backscattering field experiments for snow and other bright materials.

2 This thesis

The main objective of this thesis is to evaluate and improve the methods of phase curve interpretation to develop a more effective tool in the study of the surfaces of planetary objects. The emphasis is on the experimental approach, which is essential in improving the big picture of the opposition effect in general and, in particular, the physical characteristics related to it. The present interpretations of the opposition peak mostly derive from computational models, leaving many open questions, which could be tackled in the laboratory. In more detail, the study aims to:

- Sort out, from somewhat scattered field of study, what can be recovered from phase curves and what is still not known. This includes the evaluation of existing observations.

- Discuss the problems encountered in the phase curve study, and provide some guidelines for solving them (at least to point out the direction to be headed into).

- Highlight the importance of laboratory work as an interpretation tool. This includes a development of an instrument for measurements of better accuracy and coverage.

- Evaluate and develop further the empirical interpretation methods, which together with experiments are intended to bring more effect into the study.

- Specially: application of these methods to snow and ice, the field study of which has special problems to be dealt with, and for which the backscattering behaviour is poorly known.

2.1 Summary of papers

Paper I

Kaasalainen, S., K.Muinonen, and J. Piironen 2001. Comparative study on opposition effect of icy solar system objects. *J. Quant. Spectrosc. Radiat. Transfer* **70**, 529-543.
The purpose of this paper was to evaluate the available photometric phase curves for icy Galilean satellites and rings of Saturn and Uranus by means of an empirical modelling method, and also to test the method and its suitability for intensity phase curves. The method was based on exponential-linear function combined with a statistical analysis to find the best fit. Peak properties could be classified for the best sets of data, but most of the data were insufficient in accuracy and coverage. A feasibility study was carried out to find some lower limits for number of data points required for reliable fitting (at this point, however, the study suffered of somewhat unrealistic error estimation and was revised in a later paper). Preliminary qualitative test of shadowing and coherent backscattering codes using indirect fitting was also presented. The major part of the work for the paper was my contribution: I carried out the fits, partly using and combining existing computer codes such as fitting routines by Press *et al.* (1994) and light scattering codes (Muinonen 2002 and refs. therein), in the development of which I have not been involved.

Paper II

Kaasalainen, S., J. Piironen, K. Muinonen, H. Karttunen, J. Peltoniemi, and J. Näränen 2002. Experiments of backscattering from regolith-type samples. In *6th Conference on Electromagnetic and Light Scattering by Nonspherical Particles* (B. Gustafson, L. Kolokolova, and G. Videen, Eds.), pp. 143-146. Adelphi, MD.
An instrument for backscattering measurements was built, especially to provide controlled measurements at and very near zero phase. This paper presented the beginning of the laboratory work: the instrument and preliminary results (which were compared with some earlier works). The experiment is one of the few simulations of the opposition effect at phase angles this small. I carried out most of the work on the article, being mainly responsible for the development and setting up of the instrument and particularly its calibration, as well as the measurements.

Paper III

Kaasalainen, S., J. Piironen, K. Muinonen, H. Kartunen, and J. Peltoniemi, 2002. Laboratory experiments on backscattering from regolith samples. *Appl. Opt.* **41**, 4416-4420.
As a continuation to the previous paper, this paper gives a more accurate description of the laboratory instrument and its calibration (and problems related to it). Experiments on meteorites were carried out, being among the first measurements at zero phase for natural samples. The preliminary results were found to agree with previous works, indicating that the device is capable of controlled laboratory study, and the first results could be the beginning of systematic data collection (to be extended far further in the future). Again I did most of the work on the article, from the measurements (I gratefully acknowledge the participation, vital ideas, and company of the other authors) to photometric reductions and calibration.

Paper IV

Muinonen, K., J. Piironen, S. Kaasalainen, and A. Cellino 2002. Asteroid photometric and polarimetric phase curves: empirical modelling. *Mem. Soc. Astr. It.* **73**, 716-721.
This article refined the empirical modelling method based on the exponential-linear function and the statistical algorithm, previously applied to satellites in Paper I, extended it to polarimetric phase curves, and implemented the method for asteroid 1 Ceres as an example. The photometric and polarimetric phase curves for Ceres could be determined with a reasonable accuracy. This work continued in Paper V. My personal contribution to this paper was in bringing the idea to practice: I provided the results for 1 Ceres, by producing a computer code for the integration of the probability distribution (using, e.g., some existing least squares codes and tools) and carried out the computations and fits of the function to the data presented.

Paper V

Kaasalainen, S., J. Piironen, M. Kaasalainen, A. Harris, K. Muinonen, and A. Cellino 2002. Asteroid photometric and polarimetric phase curves: empirical interpretation. *Icarus*, in press.
In this study, the empirical approach to phase curve interpretation based on laboratory experiments and the empirical modelling method was discussed further. Application to the available asteroid phase curves was presented. The exponential-linear function, together with statistical inversion (i.e. probability densities of parameters) describes well the phase curves, but better phase angle coverage and accuracy are necessary, especially in polarimetry. More observations were called

for: a table was presented for the objects for which an addition of just few points would crucially improve the coverage. It was emphasized that the interpretation of phase curves should not be based on modelling only, but an extensive library of related laboratory measurements is essential. Discussion of some problems in recent phase curve interpretation and some evaluation of limitations of information contained in the phase curves was put forth. I did most the work on this article, but made use of many ideas and insights from the other authors.

Paper VI

Kaasalainen, S., H. Karttunen, J. Piironen, J. Virtanen, A. Liljeström, and J. Näränen 2002. Backscattering from snow and ice: laboratory and field measurements. *Can J. Physics*, in press.
Ice being one of the major issues in this thesis, the first results on field work of snow with the backscattering laboratory instrument were produced as an effort to get insight into backscattering from icy samples. Major problems related to field study were discussed, as well as some special requirements for the instrument to suit better for the purpose. A rough classification of the snow samples was made along the lines established by Colbeck *et al.* (1985). Two earlier experiments were also reported, and all three results suggested the existence of brightness peak for snow and ice, which was observed to grow with increasing contamination. Further studies are essential to understand better the connection of snow types and optical properties, where these pioneering works can act as a beginning. My contribution: I participated in the two earlier experiments though the setups were designed by others. I was responsible for the whole third experiment, though group work was essential in setting up the laboratory instrument for field purposes, snow sampling, and the measurements. I completed the data reduction and the interpretation of the results of all experiments as well as the rest of the work.

2.2 Methods

2.2.1 Experiments

The laboratory device for backscattering measurements is sketched in Fig. 2. The non-polarized light from a laser first passed a linear polarizer and was then partly reflected down to the sample by a beamsplitter (see Fig. 3). The scattered beam from the sample again passed the beamsplitter, another linear polarizer, diffuser (to cut out the laser speckle), and collimator before hitting the detector. By turning the beamsplitter (as denoted in Fig. 2 right), the reflected laser spot on the sample moved towards the laser, thereby changing the incidence and phase angles. Test measurements were carried out for powders that have been used in earlier small-

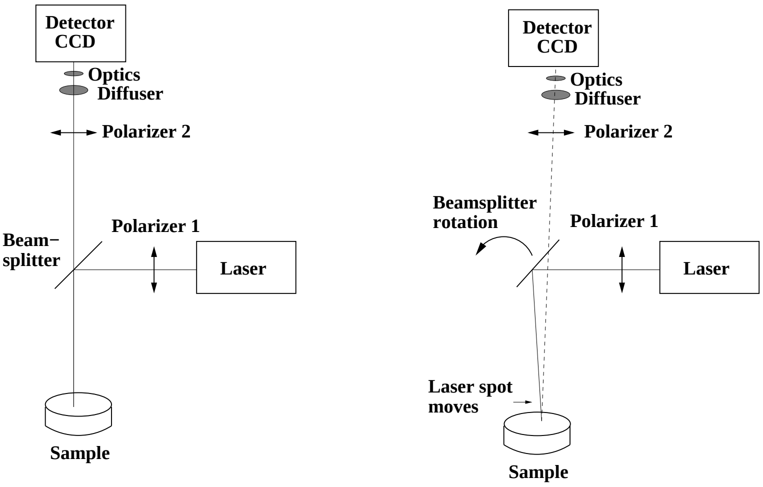

Figure 2: The backscattering experiment at zero (left) and nonzero (right) phase angle. The beamsplitter was rotated around its mounting post to change the scattering geometry.

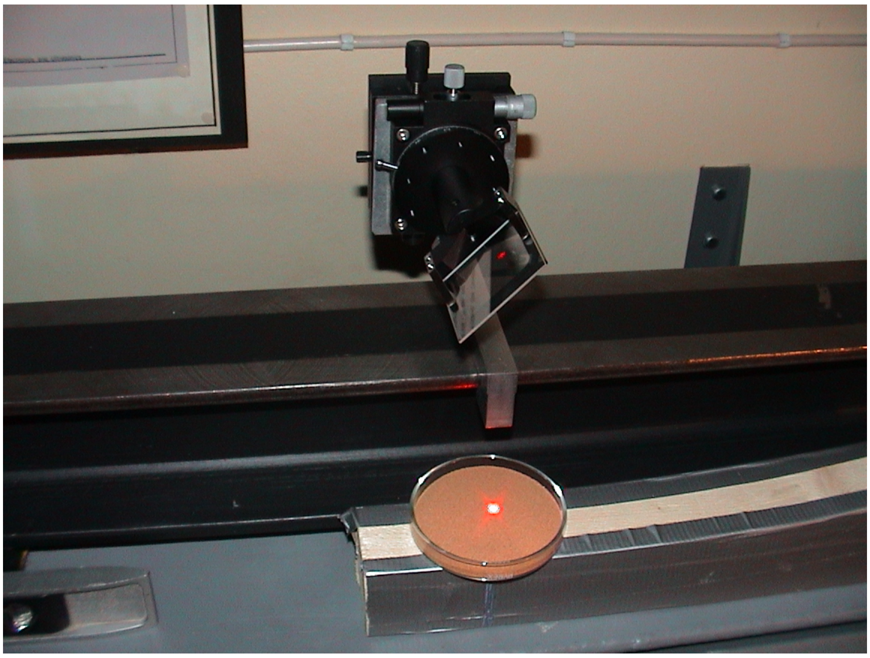

Figure 3: Laser spot on a sample of Sahara sand reflected from the beamsplitter. (Photograph by Jean-Luc Josset and Stephane Beauvivre, SPACE-X.)

phase angle experiments (e.g. Nelson *et al.* 2000, Shkuratov *et al.* 2002) so that these could be compared. To start collecting data from natural samples, photometric phase curves for Sahara sand with known grain size and meteorite rocks of varying albedo were measured. Both cross- and co-polarized[5] phase curves were measured, but problems in determining more accurately the polarization characteristics of the beamsplitter prevented the derivation of the degree of linear polarization at each phase angle. The linear polarizers were not used in the snow field experiment, the setup being otherwise similar.

Besides the scattering measurements, an important part of the field work was the classification of the snow samples. From earlier experience in geophysics, this was carried out most effectively by visual means, using e.g. scaled magnifying glasses.

2.2.2 Empirical modelling

The exponential-linear function used in empirical fitting of phase curves was simplified in the course of this study, finally to end up in the form (α being the phase angle):

$$f(\alpha) = a\exp(-\frac{\alpha}{d}) + b + k\alpha \ . \tag{5}$$

In photometric application, $f(\alpha)$ is the relative intensity, a is the height and d the width of the brightness peak, and b is the background intensity. For polarimetry, $f(\alpha)$ is the degree of linear polarization, a is an amplitude coefficient, d the angular scale of the polarization surge, and b is the balancing amplitude coefficient. In both cases, k is the slope of the linear part. In fact, the shape of the phase curve can be described with only three parameters, using b only for scaling purposes.

The main interest of this study was laid in the backscattering parameters. The probability density p for peak parameters a and d was obtained from the probability density of four parameters by integration with respect to b and k:

$$p(a,d) \propto \int_{k_1}^{k_2}\int_{b_1}^{b_2} dbdk\sqrt{\det A}\exp[-\chi^2/2] \ , \tag{6}$$

where A is a matrix containing the partial derivatives with respect to the four parameters, and χ^2 is the obtained minimum of least squares fit of the parameters (see Press *et al.* 1994, p. 665). The procedure was implemented in practice as follows: for each dataset, rough estimates for initial values of a and d were searched for, to determine roughly the parameter ranges to be scanned through. A two dimensional evenly spaced grid was formed, where each point corresponded

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[5] **Cross-polarized:** linear polarizers in opposite directions to each other. **Co-polarized:** both polarizers in the same direction.

to certain values of a and d (this grid was often changed, however, if no maximum was found in the computed probability distribution). At each point, best values of b and k were fitted to determine their integration limits, after which p could be computed. In this way, the search can be extended beyond local minima of least squares close to the initial values, and the parameters corresponding to the maximum value of the distribution well represent the best fit of the exponential-linear function to the data.

2.3 Results and discussion

Thus far, phase curve study has mostly been based on measurements of miscellaneous objects and complicated multiparameter modelling. Attempts at understanding and interpreting the phenomena have been made almost exclusively via hypotheses derived from theories. The related ideas work well computationally, and most models reproduce nicely the known characteristics, but more work is needed to improve their input in understanding and predicting the nature of remote (unknown) objects. This thesis introduces a practical approach in order to make the interpretation more effective in terms of experiments and more reliable inversion. The main results of the work done can be summarized as follows:

- The development of a laboratory instrument, which is capable of producing phase curves on relative intensity, enabling the acquisition of controlled zero-phase data to study the shapes of backscattering peaks. Further work is required for negative linear polarization. Preliminary results on meteorites suggested that the measured peaks grow sharper with increasing reflectivity.

- The method for empirical modelling was outlined and optimized. The phase curves can be expressed in an exponential-linear form, and the best fit can be found. The method is useful in qualitative and comparative classification.

- The available and appropriate photometric and polarimetric phase curves for asteroids, icy Galilean satellites, Saturnian and Uranian rings, and some laboratory samples have been evaluated (in terms of their coverage and accuracy for reliable interpretation). More data is needed for most objects to get conclusive results and achieve a better link between phase curve properties and surface texture.

- Preliminary backscattering results were achieved for snow and ice, indicating an increase in peak with decreasing albedo, challenging the coherent backscattering explanation of the peak. The work is still at the outset, and the key factors in backscattering are yet to be determined for icy samples.

Since a well-established remote sensing method still requires effort, the experiments must be repeated several times to minimize the effects of errors and misconceptions in their interpretation. The experimental information is powerful only as a large database, again requiring repeated experiments by several contributors. Even though perfectly controlled samples, especially those of small grain size, are not always possible, variation of the crucial parameters is possible with less control. For instance, the effects of grain size and porosity can be mapped without knowing exactly the particle shapes. Improvements of the device presented in this thesis should be focussed on better alignment and suitability for each target, keeping in mind the simplicity and portability for field purposes.

Terrestrial snow appears as is, with limited possibility to a priori variation of crystal properties. Therefore a large database for many snow types has to be measured: several measurement campaigns to different regions with varying weather conditions should be arranged, to find different snow types. This would gradually increase the supply of phase curves, enabling a comparative study of e.g. (average) crystal sizes and shapes. The work on snow presented in this thesis is a starting point of this work. Even though systematic test measurements with better controlled samples than snow are of greatest importance at this point, natural samples are important since they specify and give insight into the questions under consideration.

Some of the presented and previous experiments have brought forth some effects that seem to be in contradiction with predictions by models (e.g. Poulet *et al.* 2002, Nelson *et al.* 2002). Some of these may eventually find their explanation in the context of currently understood mechanisms, but further testing of physical models by experiments should be carried on. Agreement of models with experiments (rather than only with each other) is essential for the progress of this field, especially since many current models have gone far beyond what we know from experiments. Some of the models have not been tested experimentally, or have only been successfully fitted to one or few phase curves. This again emphasizes the importance of ample supply of laboratory data in more extensive testing of models before large applications for remote objects. Well tested physical models would be a valuable contribution to a better understanding of the observed effects, even though further search for models better suitable for inversion still had to continue.

There are some further aspects to consider when evaluating the suitability of phase curve interpretation as a remote sensing tool: 1) The opposition peak and the negative polarization surge are relatively simple features. Empirical models have turned out useful because of their simplicity, and might remain among the most powerful tools in the interpretation of simple characteristics. 2) Perhaps the output of physical models is better for data that spread over the whole range of scattering (or phase) angles, incidences, and azimuths, or in e.g. BRDF spectroscopy, revealing more features than a single peak. Grenfell *et al.* (1994) used Mie theory combined with multiple scattering, and concluded that a simplified model could describe the spectral albedo of a snowpack. 3) The information in disk-integrated phase curves is limited. Satellites have varying regions (in e.g. albedo and surface roughness) and a disk-integrated phase curve shows a combined effect of all these regions. However, disk-integrated phase curves may remain the only source of information for those objects for which spacecraft data is not available. Relations between disk-integrated and disk-resolved curves could be studied in laboratory (e.g., by obtaining disk-resolved photometry at different scales of resolution from systematic combinations of various regolith materials), to find out to what extent disk-integrated data can be interpreted.

3 Conclusions and future work

This study has aimed at a more effective, more practical, and more conclusive approach of phase curve interpretation, which could improve the present understanding of the textural properties of the surfaces of small solar system objects.

The laboratory results presented here are some of the first laboratory simulations of the opposition effect at zero and very small phase angles. These results represent the outset of an extensive *in situ* study of the opposition effect, which has been reasoned to be essential for the evaluation and interpretation of remote data and for the search for and testing of predictive models.

Efficiency is added to inverse techniques by utilizing a statistical approach, to minimize ambiguity in the parameters obtained. The use of an empirical function could be improved in the future by establishing a stronger connection between fitting parameters and physical characteristics. As pointed out in the study, this connection is not possible without further experiments and better telescopic or spacecraft data.

The zero phase angle measurements of ice are to the best of my knowledge the first in this field. Thus far the backscattering field measurements for icy samples are so few and sparse that every phase curve is a novel and significant addition to the current knowledge. Insight into the optical properties ice, also in backscattering, is an important contribution to the Finnish snow and ice study, providing another remote sensing scheme.

Despite the discussed limitations of information contained in the phase curves, the study of the opposition effect has future prospects of developing into a powerful remote sensing tool to be combined with other well established methods. For this, the focus of the phase curve study must be shifted from non-conclusive interpretations to a stronger experimental approach. This thesis has taken some steps towards that objective.

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