

Laboratory photometry of planetary regolith analogs

I. Effects of grain and packing properties on opposition effect

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Abstract. New laboratory phase curves are presented to act as ground truth for solar system regolith photometry. The effects of physical parameters such as grain size, surface roughness, and packing density on backscattering peak can be recognized, but it turns out that the same parameter may have different effects depending on the sample, and the parameter effects are mixed with each other. These are a strong limitations to modelling, since the scattering models usually do not distinguish between compositions or predict different effects of same parameters. Furthermore, attention should be paid not only to physical but chemical characteristics as well. This emphasizes the role of experiments in the study of the opposition effect and surface characterization. As the experimental approach to scattering study becomes more significant, the laboratory methods for backscattering must be constantly improved to suit better the remote sensing purposes and achieve a large database.

Key words. planets and satellites: general – minor planets, asteroids – scattering – methods: laboratory

1. Introduction

Laboratory photometry of regolith-type samples is essential to the interpretation of phase curves, which are being used as a planetary surface characterization tool. The effects of physical parameters on a simple peak-type feature are neither well understood nor adequately described by most theoretical models. The current physical interpretation of the opposition effect (a brightness surge near zero phase angle) is based on two phenomena: shadowing and coherent backscattering (Hapke 2002; Shkuratov et al. 2002; Muinonen et al. 2002; Mishchenko et al. 2000), but none of these models is yet suitable for effective inversion.

Coherent backscattering has been widely studied in laboratory at a very narrow angular range (see Kaasalainen et al. 2002 for a review). Several case studies on the opposition effect are also available to complement the computational studies, but without conclusive parameter variation. Some laboratory studies of the influence of parameters on the opposition effect have been made, e.g. the effects of albedo, particle size and wavelength have been studied (Hapke et al. 1993; Nelson et al. 2000, 2002). Shkuratov et al. (2002) mostly compare two different cases for each parameter. Another interesting qualitative study is made by Oetking (1966). It has not been experimentally established whether, or how extensively these results can be generalized for other types of samples. Little or no laboratory studies exist on some parameters, especially surface

roughness and packing density, which have thus far been addressed mostly theoretically. Experimental testing of models is also at the outset and most models have not been tested at all. As more and more disk-resolved data have been made available by spacecraft, laboratory studies become more comparable with remote data. An extensive photometric (and polarimetric) database will constitute a ground truth for more reliable interpretation of phase curves. Such a database requires numerous experiments and can hence be collected only little by little, but it will increasingly contribute to more accurate knowledge of the surface properties of minor planets and satellites and hence the structure and evolution of the solar system.

This article presents some new laboratory results to study the effects of such parameters as grain size, surface roughness and packing density. I also supply a brief discussion on the constraints and limitations of the backscattering laboratory methods, which seem to be the major cause for the limited number of experimental data.

2. Measurements

Working with unpolarized (i.e. random polarized) He–Ne laser causes fluctuations in linear polarization (and practically prevents the measurement of the degree of linear polarization). Other type lasers are linearly polarized to some extent. Using a non-coherent light source would cause alignment problems and restrict the use of the beamsplitter in this type of setup, where the phase angle changes with the moving laser spot. Light reflection from surfaces (such as beamsplitter) and transmission

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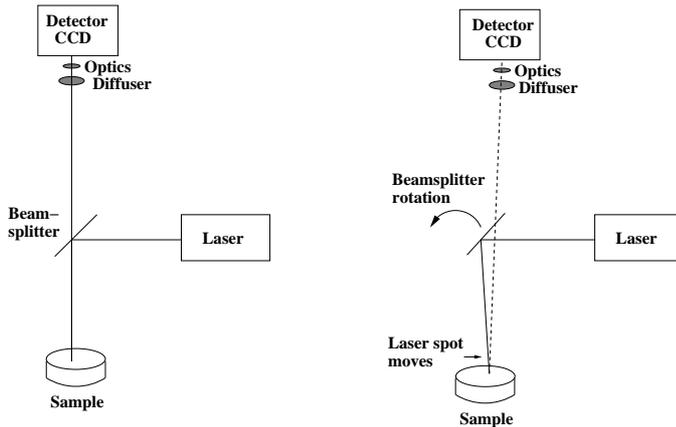


Fig. 1. The experiment setup at zero (left) and nonzero (right) phase angles. The distances from the beamsplitter to the detector and to the sample were approximately 150 cm and 20 cm, respectively.

through filters changes the polarization and introduces uncertainty in the absolute intensity measurement. Relative photometry is however possible even if the beam can not be entirely depolarized, and the parameter effects to backscattering peaks can still be compared. Furthermore, many applications (as in terrestrial remote sensing) also work with more or less polarized light sources. Taking polarization into account is a future objective of this study. Further work is also necessary for eliminating the possible uncertainty at exact zero phase, due to reflections from lenses and other components.

A more accurate description of the instrument prototype is given in Kaasalainen et al. (2002). The setup in the present paper has been improved with respect to the beamsplitter alignment and minimizing the polarization effects, for which a non-polarizing plate beamsplitter is used. The beamsplitter of this type gives a better accuracy when no polarizers are used, but it is somewhat angle-sensitive at large angles of incidence, and requires extra calibration for the angle of incidence. This was done with the aid of a Spectralon panel, the phase curve (i.e. the directional scattering properties) of which is somewhat flat at larger phase angles, which correspond to large incidence angles on the beamsplitter. The setup for the basalt samples had a 10% transmission filter in front of the 632.8 nm He–Ne laser (the setup is sketched in Fig. 1). The reflected beam from the sample passes through the beamsplitter before the CCD detector, where a diffuser was used to kill the laser speckle. The rotation of the beamsplitter enabled phase angle variation as the incidence to the sample changed. For the white samples (Al_2O_3 and icing sugar) a 0.01% filter was used for longer exposures to minimize deviation. Despite the improved optics and alignment, the intensity at zero point may still be slightly disturbed by extra reflections and light going back to laser etc. Therefore the first nonzero point is used in the phase curve comparison in Tables 1–3.

The mineral samples were basalt with olivine and oxidized basalt, both in four grain size ranges: $<75 \mu\text{m}$, $75\text{--}250 \mu\text{m}$, $250\text{--}500 \mu\text{m}$, and $500 \mu\text{m}\text{--}2 \text{ mm}$ (cf. Cord et al. 2003). These are analogs to planetary regoliths. The aluminium oxide abrasive powder (Micro Abrasives Corp.) was suitable for

Table 1. Basalt with olivine: opposition peak properties, presented as ratios of intensity at 0.2° to that at 20° (approximately) and fitted parameters (peak size $\frac{a}{b}$ and peak width d).

Grain size	$I(0.2^\circ)/I(20^\circ)$	Size	Width
$<75 \mu\text{m}$	1.25	0.18	0.9
$75\text{--}250 \mu\text{m}$	1.47	0.24	2.8
$250\text{--}500 \mu\text{m}$	1.56	0.31	2.1
$500 \mu\text{m}\text{--}2 \text{ mm}$	1.34	0.41	3.6

Table 2. Oxidized basalt: opposition peak properties, presented as ratios of intensity at 0.15° to that at 26° (approximately) and fitted parameters (peak size $\frac{a}{b}$ and peak width d).

Grain size	$I(0.15^\circ)/I(26^\circ)$	Size	Width
$<75 \mu\text{m}$	1.53	0.21	1.4
$75\text{--}250 \mu\text{m}$	1.69	0.25	2.3
$250\text{--}500 \mu\text{m}$	1.71	0.26	2.3
$500 \mu\text{m}\text{--}2 \text{ mm}$	1.76	0.35	3.1

Table 3. Aluminium oxide: opposition peak properties, presented as ratios of intensity at 0.15° to that at 24° (approximately) and fitted parameters (peak size $\frac{a}{b}$ and peak width d).

Packing	$I(0.15^\circ)/I(24^\circ)$	Size	Width
Rough ($1.12 \frac{a}{ml}$)	1.15	0.07	0.95
Smooth ($1.12 \frac{a}{ml}$)	1.16	0.13	0.85
Pressed ($1.28 \frac{a}{ml}$)	1.13	0.11	0.65
Pressed ($1.33 \frac{a}{ml}$)	1.12	0.13	1.35

compressing and packing density study due to its small grain size ($1 \mu\text{m}$). An icing sugar sample of $35 \mu\text{m}$ average grain size was measured to compare the effects of materials with different chemical structure but similarity in macroscopic properties. While poured into sample cups, the rough surface samples of aluminium oxide and icing sugar were shaken only very lightly so that the surface features remained rather coarse. For smooth samples, the surface was gently smoothed, but not pressed. Aluminium oxide was measured in a scaled cup, to be able to keep track of its volume while pressing the surface (with a plastic piston) for greater compression.

3. Results and their interpretation

All the measured phase curves (relative to Spectralon standard average at large phase angles ($>5^\circ$), where its phase behaviour is constant) are shown in Figs. 2, 3. The intensities of basalt with olivine decrease with grain size, but a clear backscattering peak is evident for all grain size ranges, as it is also for the oxidized basalt samples, for which the intensity relations are not that clear. Great deviation in data is a typical feature for the tiny grained aluminium oxide, but it evens out somewhat for smoothed surfaces. There is a clear difference in peak size between rough and smooth aluminium oxide samples: a smooth

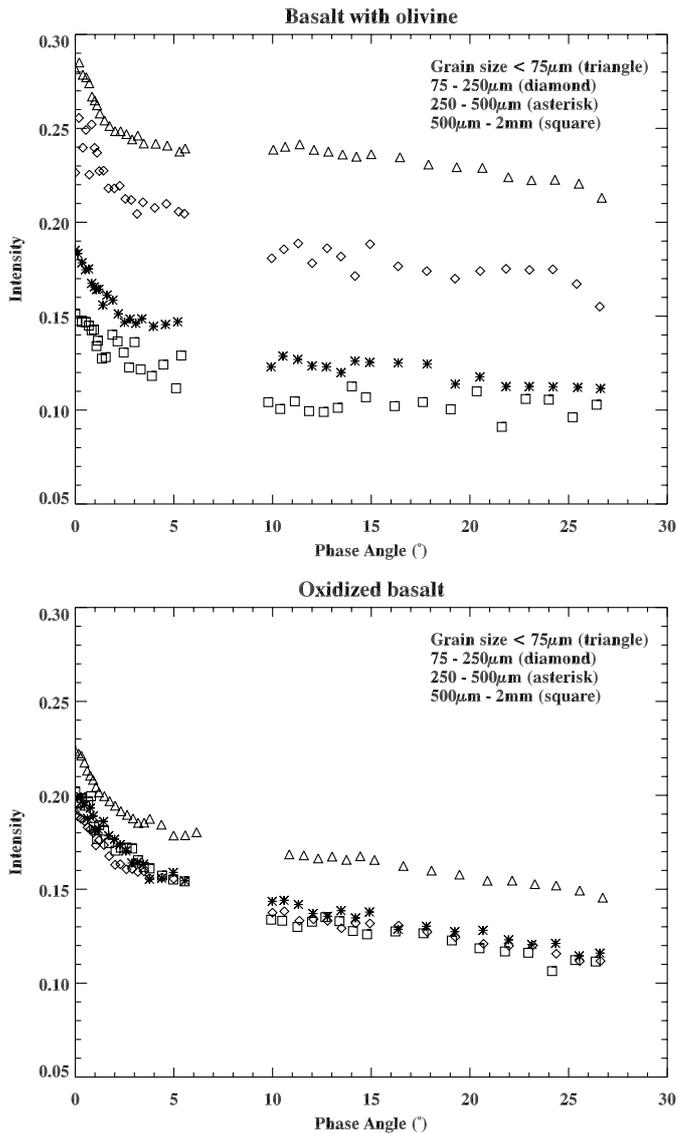


Fig. 2. Phase curves of basalt with olivine and oxidized basalt. All measurements are relative to Spectralon standard, but their relative brightnesses are comparable to each other. Each data point is an average of three measurements.

surface exhibits a sharper peak. This is in agreement with earlier preliminary measurements with similar sampling.

The icing sugar samples – either smoothed or not – show no peak in correspondence with earlier preliminary investigation with both granular and icing sugar (also cf. Oetking 1966, who found no effect for granular sugar, but a peak emerged when the sugar was frosted). The brightness (albedo) of the sugar sample is very near to that of aluminium oxide (see Fig. 3). Both samples are mainly crystalline: Micro Abrasives Corp. report their aluminium oxide powders to be platelet shape crystallites and icing sugar particles are mostly irregular crystals, though some of it (a few %) has turned amorphous during the grinding process. The aluminium oxide sample was smaller in grain size ($1\ \mu\text{m}$) than the sugar sample ($35\ \mu\text{m}$), but a phase curve of a similar aluminium oxide sample of $30\ \mu\text{m}$ and refractive index of 1.7 has shown a clear backscattering peak

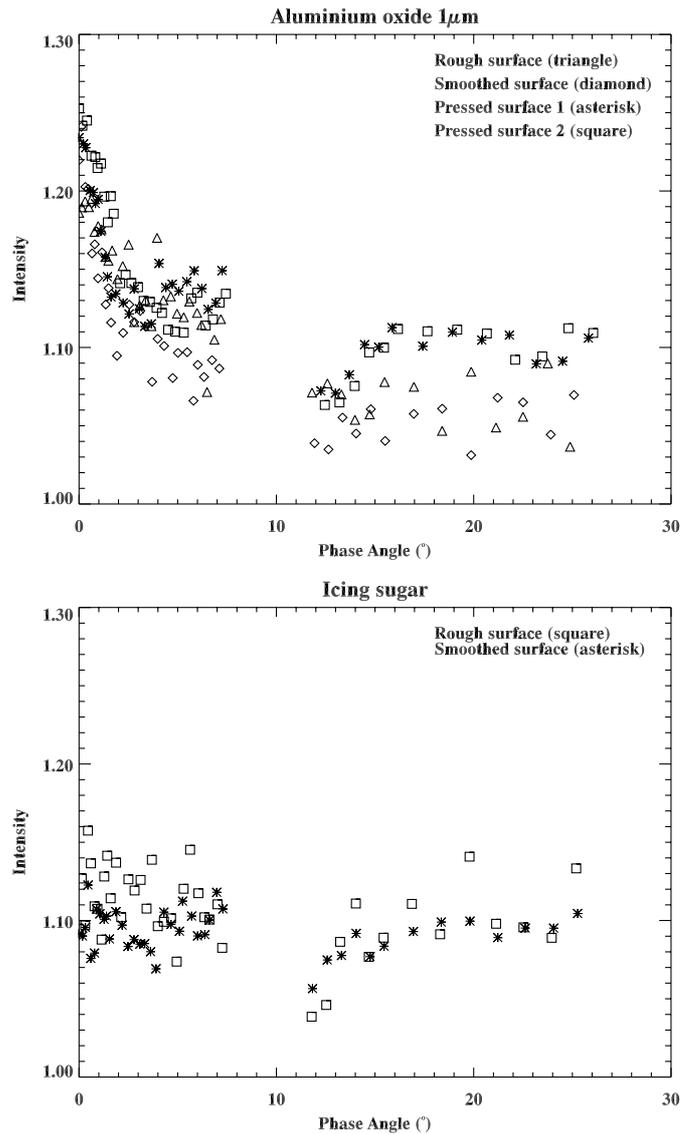


Fig. 3. Phase curves of aluminium oxide (Al_2O_3) and icing sugar. (Relative brightnesses as in Fig. 2.)

(Nelson et al. 2000). The index of refraction for sucrose is 1.5. This raises some interesting considerations: peak properties change considerably even though differences in physical properties are very small, at least to produce such material changes or even the disappearance of the peak. Either the backscattering peak is a stronger discriminator of some properties (e.g. grain shape) than others, or chemical composition dominates over all or most physical characteristics (as far as these can be separated). This is certainly a great challenge for future experiments.

To study the parameter effects on phase curves in more detail, a simple exponential function with a linear part is fitted to the data (excluding icing sugar, which shows no peak). The relative intensity $f(\alpha)$ is a function of four parameters:

$$f(\alpha) = a \exp\left(-\frac{\alpha}{d}\right) + b + k\alpha \quad (1)$$

where a is the height (amplitude) and d the width of the backscattering surge, k is the slope of the linear part, and b

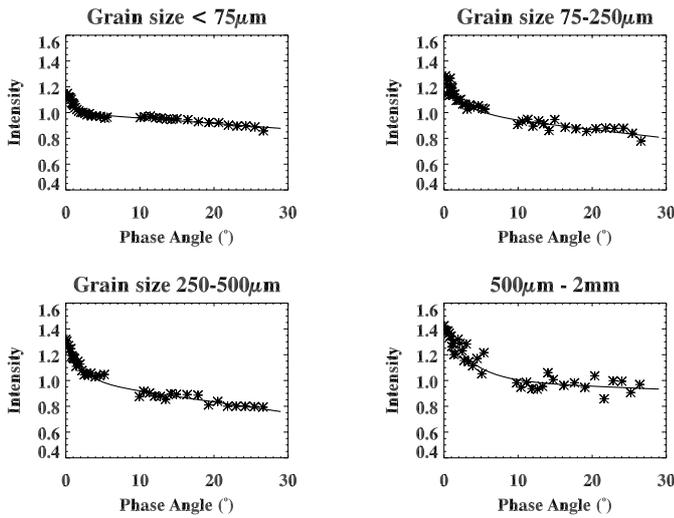


Fig. 4. Basalt with olivine: data and exponential-linear fits (the linear part interception with y -axis is normalized to unity for easier peak height comparison).

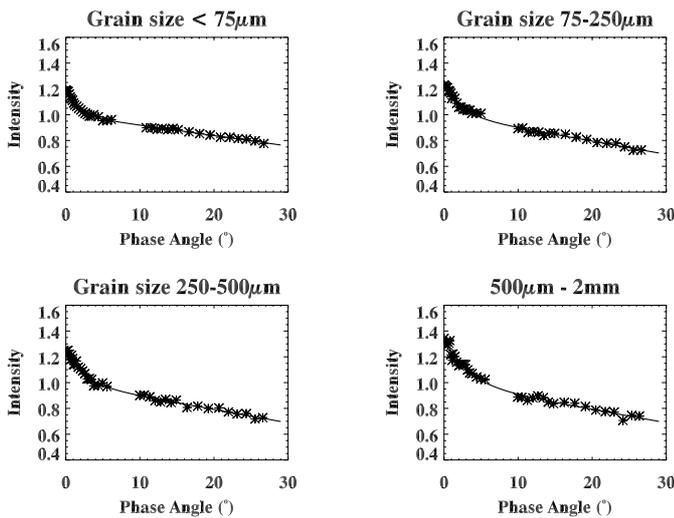


Fig. 5. Oxidized basalt: data and exponential-linear fits (normalized as in Fig. 4).

(linear part interception with y -axis) can be used for scaling and background intensity. Statistical inversion (probability distributions for backscattering parameters) is used for more reliable least squares fits. A similar approach has been used previously for empirical interpretation of asteroid phase curves (Kaasalainen et al. 2003). The fits, normalized such that the linear part intercepts the y -axis at unity ($b = 1$), are in Figs. 4–6.

Tables 1–3 summarize the surface features and their effects on the opposition peak. The peak properties are presented as fitted heights and widths of the opposition peak (exponential function parameters, see Eq. (1)). The peak size is also compared as phase ratios of the intensity near backscattering to that in the linear part of the curve, i.e., at phase angles around 20° .

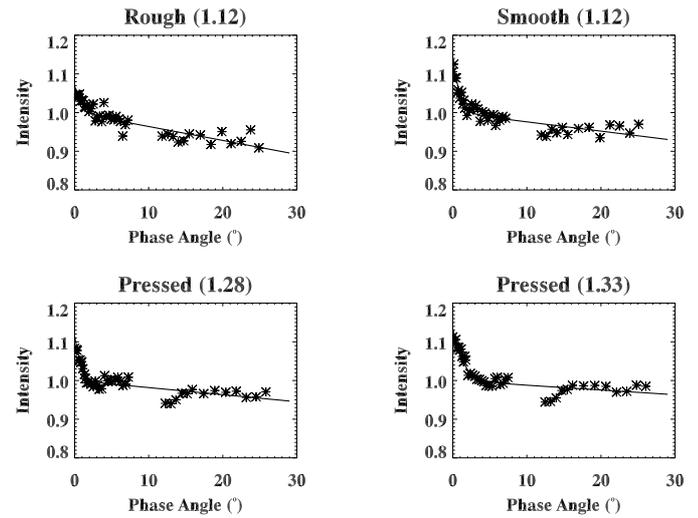


Fig. 6. Aluminium oxide: data and exponential-linear fits (normalized as in Fig. 4).

Some parameter effects are quite evident, some are rather tentative and require a further study with extended parameter range:

- Grain size (minerals): the peak size increases with increasing grain size range. The same mostly applies to peak width (with some exceptions which may arise from deviations in data which lead to inaccuracies in fitting). Experiments with much smaller grains have indicated the sharpest peak to occur at particle sizes close to the wavelength (Nelson et al. 2000), but for large grain sizes, the grain microstructure becomes more eminent.
- Surface roughness: only one case can be studied since icing sugar shows no effect whatsoever. The peak clearly increases and sharpens when the surface is smoothed. This can not be entirely explained by shadowing that is not yet large in the narrow peak phase angle range. Shadowing might however explain the negative slope (k) increase in the linear part: for rough sample $k = -0.0041$, and for the smoothed (but not packed) $k = -0.0026$.
- Packing density: three different packing densities are studied for Al_2O_3 , but no strong effect on the backscattering peak is seen. The next objective (in the forthcoming Paper II) is to extend the packing density range from nearly floating particles to hard pressed tablets, and determine whether the packing density has any strong or clear effect for different materials.
- Albedo: effect on peaks can be investigated using relative intensities. For minerals, the peak size grows with grain size and hence decreases with sample albedo. In earlier experiments the albedo relation is inverse. This might be due to a mixed effect of the two parameters, but not entirely: in previous experiments (Nelson et al. 1998; Kaasalainen 2002) the more reflective materials had stronger peaks, even for rocks or mixed particle sizes. Furthermore, the peak for Al_2O_3 seems to be narrower, but smaller in size, compared to the lower albedo minerals.

- Other surface properties: further questions have also been raised by the current and previous experiments on, e.g., grain shape, transparency (refractive index) and electric conductivity (as water solution), which seem to have a conclusive effect on both existence and properties of the (possible) backscattering peak. Chemical composition also plays a role.

4. Conclusions

1. Of the “macroscopic” properties, surface roughness and grain size seem to have the strongest effect on backscattering peak shapes. No effect of packing density was found on the first case study, but the problem will be further addressed. The effect of albedo most easily mixes with other parameters.
2. Material difference in the backscattering properties can arise even though the physical properties change only slightly. This points out to the role of chemical composition (as far as what is independent of physical properties), which has not been studied in great detail in this context since it is neglected by commonly used scattering laws.
3. These results contradict the universal nature of scattering laws: they seem to depend strongly on the media they are applied to. It may turn out, that they can be accurately derived for one material at a time, and only (semi)experimentally, at least to work in remote sensing. Results (measured or modelled) for a single sample/media cannot be too widely generalized.
4. A considerable amount of future work has to be done to determine experimental scattering laws and study the single and combined parameter effects. That work is also being extended beyond the small phase angle region (as in e.g. goniometric applications).

This study is one of the few contributions to the thus far sparse collection of experimental scattering studies that aim at the interpretation of the photometry of small solar system objects. Some effects (such as surface roughness) are pointed out only qualitatively, but even as such, they are first laboratory investigations of the particular feature. Attention should not be paid to physical characteristics only, but chemical compositions as

well. The backscattering database must be vastly increased in the future. Therefore, further experiments are in progress along with the constant improvement of zero-phase laboratory methods for more accurate data. Even though terrestrial conditions and materials can not always be compared directly, relative properties can be studied and the results applied to remote surfaces. Accordingly to terrestrial remote sensing, where ground truth is a prerequisite for reliable interpretation of space and airborne data, the remote sensing of space regoliths should increasingly rely on laboratory “ground truth” and well tested (semi-empirical) models to recover what we actually want to know about the surfaces: their microstructure and surface textural properties.

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