COHERENT BACKSCATTERING BY SOLAR SYSTEM DUST PARTICLES

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Abstract. I review progress in interpreting the opposition effect and negative linear polarization observed for solar system dust particles. The so-called coherent backscattering mechanism has recently been introduced to explain the observations. However, fundamental difficulties in theoretical modeling still prevent quantitative interpretation. I also review some of the key observations that questioned the hitherto widely accepted mutual-shadowing explanation for the opposition effect. I summarize previous theoretical and experimental work on the opposition effect and negative polarization.

1. Introduction

Close to astronomical opposition, there are two intriguing light scattering phenomena observed for solar system dust particles : the *opposition effect* and *negative linear polarization.* As for the increase of brightness, the behaviour in both narrow and wide ranges of solar phase angle is discussed. The phase angle is the angular distance between the Sun (light source) and the observer (detector) as seen from the object (sample). The wide-angle brightening from large phase angles down to about 10° is common for dark rough particulate surfaces and can be termed the *strong backscattering effect.* The narrow-angle brightening, a rapid increase in brightness towards zero phase angle, observed for phase angles lower than 10°, is generally called the opposition effect. In the present review, I do not distinguish between the opposition effect and opposition spike, the term sometimes used for "anomalously" narrow opposition effects.

The sunlight incident on solar system bodies is known to be unpolarized to great precision. The degree of linear polarization of scattered light, or briefly linear polarization, is defined as the ratio

$$P = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} , \tag{1}$$

where $I_\parallel$ and $I_\perp$ refer to the intensity components parallel and perpendicular to the scattering plane, here defined by the Sun, the object and the observer. Negative polarization is observed when the parallel component is greater than the perpendicular. This is opposite to first-order Rayleigh scattering or Fresnel reflection, which result in perpendicular, positive polarization. Typically, the observed angular ranges for negative polarization vary between 15° and 25°.

None of the existing treatments of electromagnetic scattering by inhomogeneous media is generally applicable to solar system dust. The present review is partially

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based on the following material : Muinonen (1990) on coherent backscattering, and the opposition effect and negative linear polarization, Pellicori (1971) on the history and milestones of polarimetry, Kravtsov and Saichev (1982) on double–passage effects in inhomogeneous media, Bowell et al. (1989) on the Hapke and Lumme–Bowell scattering laws, McGurn (1990) on the opposition effect and Anderson localization, Barabanenkov et al. (1991) on enhanced (or coherent) backscattering, van Tiggelen (1992) on multiple scattering and localization of light, Mishchenko and Dlugach (1993) on coherent backscattering, and Shkuratov et al. (1994) on the theoretical models for negative polarization.

Since 1887 it has been known that the brightness of the Saturnian planet–ring system peaks sharply at opposition. Using Müller's observations (1893), Seeliger (1887) assigned the phenomenon to the rings and gave the classical mutual shadowing explanation : ring particles hide their own shadows at exact backscattering geometry, which leads to opposition brightening. Lyot (1929) reported the reversal of linear polarization for the rings, but offered only rather general ideas for the origin of the phenomenon.

The strong backscattering effect was reliably observed for the Moon by Herschel (1847), who could not explain the brightening and concluded that there must have been a systematic error in the measurements. However, Herschel's observations were later confirmed by Russell (1916a), who was aware of Seeliger's (1887) theoretical considerations for Saturn's rings. Russell (1916b) further proposed that the lunar surface was covered with fragments of rock. At the moment, the main reason for the strong backscattering effect is thought to be macroscopic shadowing, or rough–surface shadowing, due to structures formed by the regolith dust particles.

The coherent backscattering mechanism has been pointed out by Watson (1969) in studies on multiple scattering of electromagnetic waves in an underdense plasma, and by de Wolf (1971) in studies on electromagnetic reflection from a dielectric turbulent medium. The relevance of the coherent backscattering mechanism to the opposition effect of the Moon was mentioned but ignored in studies of electromagnetic scattering (e.g., Kuga and Ishimaru 1984, O'Donnell and Mendez 1987). In the solar system context, it was introduced as a possible explanation for the opposition effect and negative polarization by Shkuratov (1988b, 1989) and Muinonen (1989ab, 1990). The coherent backscattering mechanism does not require any specific assumptions of particle or regolith geometry.

The coherent backscattering mechanism is described in Figure 1a, where an electromagnetic plane wave (solid line) with wavenumber $k = 2\pi/\lambda$ (λ being the wavelength) is scattered in the backward direction via several scattering elements located of the order of the wavelength to tens of wavelengths apart. The scattering elements can be individual particles, subparticles in an aggregate particle, facets on a rough solid surface, or other irregularities. But there is the companion electromagnetic wave (dashed line) that propagates through the same scattering elements in the opposite (or time–reversed) direction. These two waves always interfere constructively in the exact backward direction, but not necessarily in other directions. Averaging over a distribution of scattering element locations will result in a backscattering peak, called enhanced or coherent backscattering. The backscattering peak tends to be narrower for higher–order interactions, the average distance be-

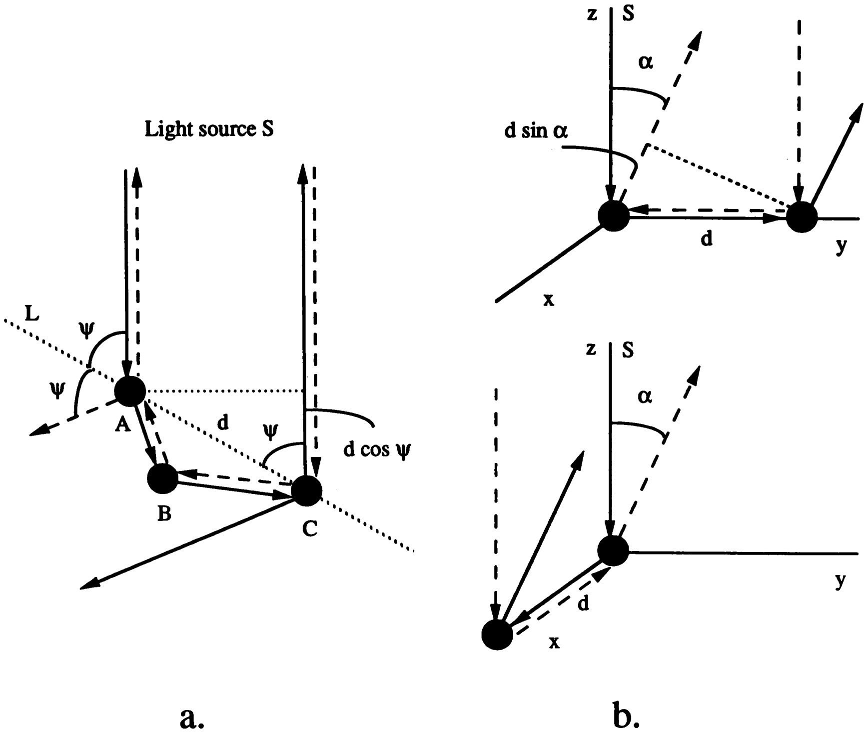

Fig. 1. (a) Opposition effect due to the coherent backscattering mechanism. The multiply scattering electromagnetic waves propagating in opposite directions (solid and dashed lines) always interfere constructively at the backward direction (phase angle $\alpha = 0°$) and in directions forming a cone with axis L. In other directions, the interference varies between constructive and destructive depending on the wavelength, and the distance and orientation of the first and last scattering elements. (b) Negative linear polarization due to the coherent backscattering mechanism. For non-zero phase angles and second-order scattering, the interference favors negative polarization : in the yz-plane in the scattering geometry leading to positive polarization the interference depends on the phase difference $\delta = kd \sin \alpha$ (upper panel), whereas the interference is always constructive in the geometry causing negative polarization (lower panel). Averaging over the element locations will result in a backscattering peak and net negative polarization.

tween the end elements increasing with increasing order of interaction.

Note that the interference is constructive in the directions of a cone defined by rotating the light source direction around the L-axis (Figure 1a) that joins the two end scattering elements—this is the key to the negative polarization mechanism. In Figure 1b, an electromagnetic plane wave is scattered via two scattering elements at a distance d from each other. The negative polarization can be understood by calculating the phase differences in the yz-plane in the two scattering geometries (upper and lower panels). Since first-order scattering is predominantly positively polarized (e.g., Rayleigh scattering and Fresnel reflection) the scattering elements sufficiently far away from each other ($kd \gg 1$) interact mainly with the electric field vector perpendicular to the plane defined by the source and the scattering elements. The observer in the yz-plane will measure positive polarization from the geometry in the upper panel of Figure 1b, and negative polarization from the geometry in the lower panel. However, the positive polarization suffers from the phase difference $\delta = kd \sin \alpha$, whereas the phase difference for the negative polarization is zero for all phase angles. Isotropic averaging over positions of the scattering centers will result both in an increase of the brightness and in a reversal of polarization near the backward direction (at exactly zero phase angle the polarization goes to zero). Scattering orders higher than the second can also experience preferential interaction geometries, and lead to net negative polarization.

As an example, Figure 2 shows the backscattering peak and negative linear polarization in total diffuse scattering for a simple scattering system of a small dipole particle close to a semi-infinite electromagnetically homogeneous medium.

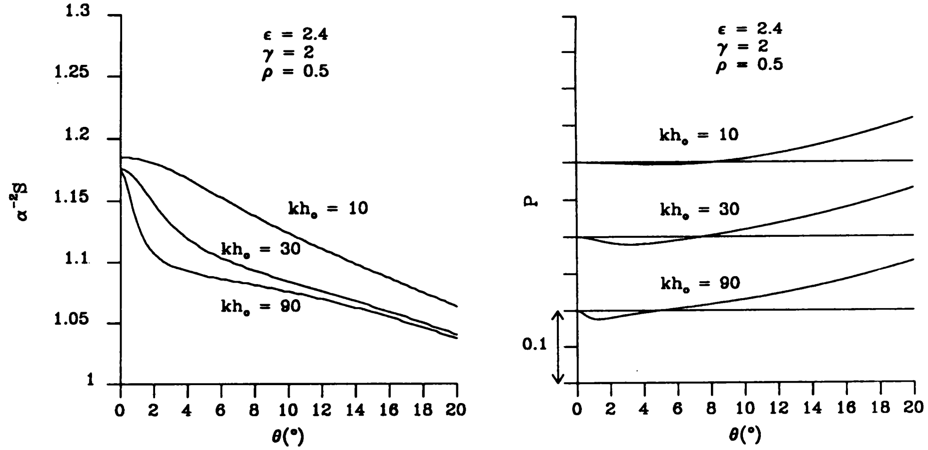

Fig. 2. Total diffuse scattering by a small dipole particle close to a material interface (Muinonen et al. 1991). (a) The coherent backscattering peak, and (b) the accompanying negative linear polarization. ϵ is the electric permittivity of the particle and the semi-infinite medium, γ and h_0 are the power and the mean in the Gamma distribution for the distance between the particle and the interface, and ρ is the standard deviation for the Gaussian random slope of the scattering system.

Another phenomenon related to brightness variations of asteroids and other atmosphereless solar system bodies is the color opposition effect (Mikhail 1970). For example, the Moon is bluest at the time of its full phase. In fact, if the optical parameters of the surface coincide for two wavelengths, the coherent backscattering mechanism predicts a narrower opposition effect for the shorter wavelength. This is in agreement with the lunar color opposition effect. However, the color opposition effect of the solar system dust particles needs further observational verification.

The coherent backscattering peak and negative linear polarization generally depend on refractive index. For small real refractive indices, the multiple scattering contribution is driven toward high scattering orders, and one can expect sharper backscattering phenomena than for larger real refractive indices. Increasing absorption decreases the lengths of the interaction paths, thus broadening the backscattering peak. On the other hand, for metallic materials with complex refractive indices, the dependence becomes more difficult, since the backscattering phenomena can sometimes be affected by electromagnetic surface wave (or surface polariton) interactions, besides the multiple reflections between different surface elements.

The coherent backscattering mechanism is a possible explanation for some observations by Sir Isaac Newton in 1730. In attempting to understand light scattering by rough surfaces, Newton faced the very same difficulties as did researchers to come (Newton 1952) :

> *There is no Glass or Speculum how well soever polished, but, besides the Light which it refracts or reflects regularly, scatters every way irregularly a faint light, by means of which the polish'd Surface, when illuminated in a dark room by a beam of the Sun's Light, may be easily seen in all positions of the eye. There are certain Phaenomena of this scatter'd Light, which when I first observed them, seem'd very strange and surprizing to me.*

In one of Newton's numerous experiments, the Sun shone into his darkened chamber through a hole in a white opaque paper chart, one third of an inch wide. The sunlight was then normally incident on a spherically concave mirror, with the radius of curvature of five feet eleven inches, and with a quick–silver coating on the convex side. The distance between the paper chart and the mirror surface was about six feet. Newton writes about the scattered light he noticed in his detector, i.e., on the opaque chart :

> *...there was, in their common center [of rainbows] a white round Spot of faint Light, something broader than the [specularly] reflected beam of Light, which beam sometimes fell upon the middle of the Spot, and sometimes by a little inclination of the Speculum receded from the middle, and left the Spot white to the center.*

The Spot around the backscattering direction can be coherent backscattering from the rough interface between the glass and quick silver. It can result from Anderson localization of polaritons by the roughness of the surface. There is debate whether the enhanced backscattering by certain metallic surfaces is predominated by multiply reflected electromagnetic waves, cyclically propagating surface polaritons (leading to coherent backscattering), or double–passage of individual surface polaritons.

In Section 2, I summarize the observations of the opposition effect and negative linear polarization for solar system objects. Section 3 reviews theories and experiments in the era before the introduction of the coherent backscattering mechanism. Research on the coherent backscattering mechanism is then reviewed in Section 4, and discussion follows in Section 5.

2. Observations

The opposition effect and negative linear polarization have been confirmed for the planets Mercury and Mars, the Moon, and the Martian, Jovian, and Saturnian satellites. The phenomena have been observed for asteroids, Saturn's rings, and for the interplanetary dust, in which case the opposition brightening has been called the Gegenschein. Additionally, the opposition effect has been observed for the Uranian satellites, and the negative polarization for cometary dust. The review of observations is here constrained to the Moon, Saturn's rings, asteroids (44) Nysa, (64) Angelina, (165) Loreley, (419) Aurelia, and the Galilean satellite Europa. Both the opposition effect and negative linear polarization have been experimentally verified in laboratory measurements for rough and particulate surfaces.

The opposition effects and negative polarizations are shown collectively in Figures 3 and 4 in the order of downward steepening slope of the linear part of the magnitude phase dependence. The slope can be related to the amount of multiple scattering so, upward in Figures 3 and 4, the objects are principally brighter. However, Saturn's rings probably consist of particles whose geometric albedos exceed those for the asteroids (44) Nysa and (64) Angelina, and also, there are hints that (64) Angelina can be slightly brighter than (44) Nysa. Unfortunately, there are no published polarization observations for (165) Loreley and (419) Aurelia. The reader is encouraged to consult the original references for information on the geometric albedos, and spectral bands for the magnitudes and polarizations.

As for Saturn's rings, the phase angle range covered with Earth-based observations is rather narrow, and the reversal of linear polarization into positive values is not seen. There is discussion whether the polarization tends to zero at zero phase angle for Saturn's rings. The sharp polarization surge for Saturn's rings can be called the polarization opposition effect (Mishchenko 1993).

Gehrels (1956) confirmed the nonlinear opposition brightening (magnitude scale) for the asteroid (20) Massalia, and introduced the term "opposition effect". The lunar opposition effect was then pointed out by Gehrels et al. (1964) and by van Diggelen (1964), although it was already discovered by Barabashev (1922) and Markov (1924), and could be distinguished in Rougier's extensive observations (1933). In short, the Moon is roughly twice as bright at opposition than on the day just before or just after opposition. Hapke (1966) interpreted the effect using the mutual shadowing mechanism, after constructing a new shadowing function for the lunar strong backscattering effect (1963). The negative linear polarization was discovered for the Moon by Lyot (1929).

Brown and Cruikshank (1983) published intriguingly sharp opposition surges for the Uranian satellites, the surge amplitudes closing a factor of two (the maximum enhancement factor from mutual shadowing or coherent backscattering as separate

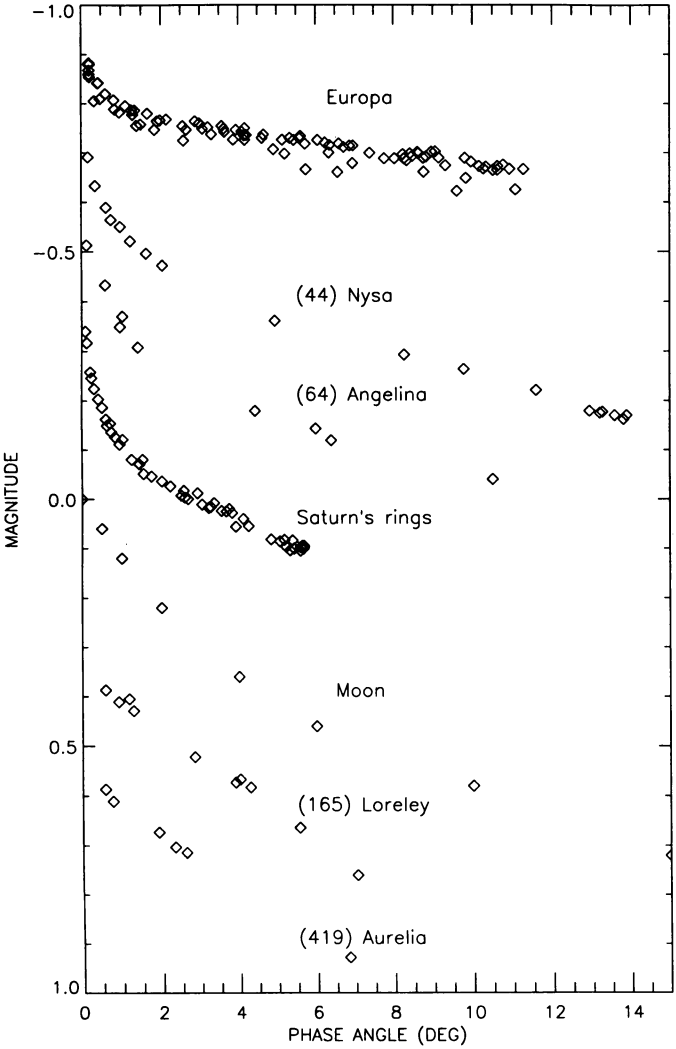

Fig. 3. The opposition effects for the Galilean satellite Europa (Thompson and Lockwood 1992), the E–type asteroids (44) Nysa and (64) Angelina (Harris et al. 1989), Saturn's rings (Franklin and Cook 1965), the Moon (Rougier 1933, Bowell et al. 1989), (165) Loreley (Harris and Young 1988), and (419) Aurelia (Harris and Young 1989). For clarity, the phase curves have been shifted using the following constants in magnitude scale (from Europa downwards) : −5.9, −7.6, −8.1, 0.09, −0.85, −7.55, and −7.95.

mechanisms). Prior to these observations, only Saturn's rings had been known to exhibit a comparable brightness surge.

Thompson and Lockwood (1992; see also Domingue et al. 1991) discovered the

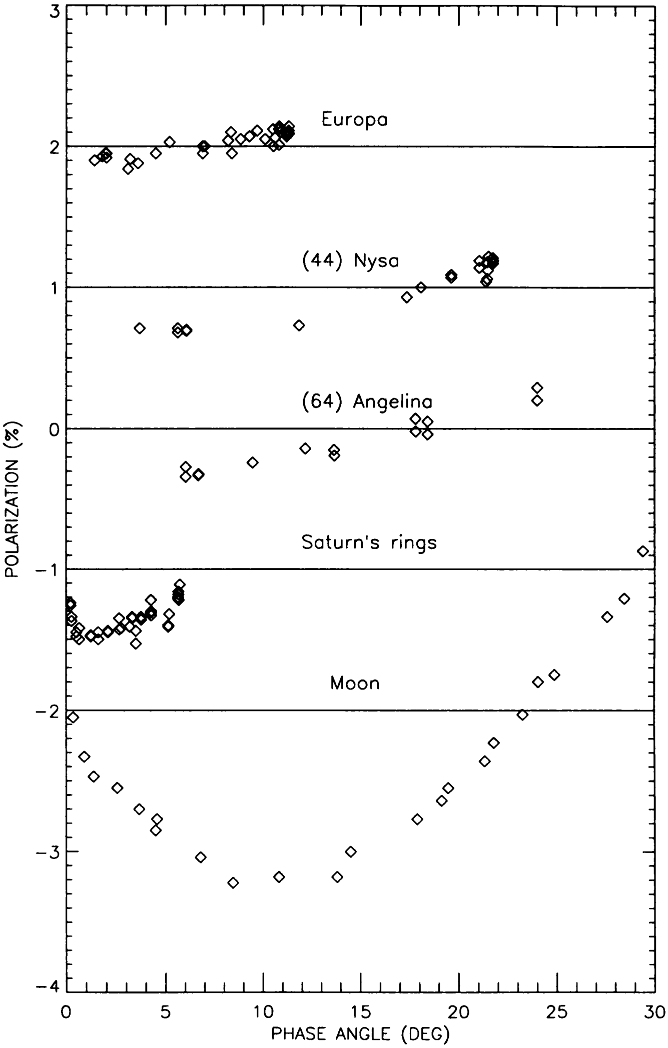

Fig. 4. The linear polarizations for the Galilean satellite Europa (Dollfus 1975), the E–type asteroids (44) Nysa and (64) Angelina (Zellner and Gradie 1976), Saturn's rings and the Moon (Lyot 1929). For clarity, the polarization phase curves have been shifted using the following constants (percentage points, from Europa downwards) : 2.0, 1.0, 0.0, −1.0, and −2.0.

record–setting sharp opposition surge for the Galilean satellite Europa in late 1986. An important observation was made by Harris et al. (1989), who measured an unusually sharp opposition effect for the bright E–type asteroid (44) Nysa. The other E–type asteroid (64) Angelina was found to exhibit a sharp opposition effect, too.

These observations raised another problem for a pure mutual shadowing explanation : how could a particle volume fraction of the order of 1% be understood for the regolith of an asteroid? In fact, these opposition effects resemble that for Saturn's rings (Harris et al. 1989).

Harris and Young (1988) have reported on dark asteroids with very small opposition effects. The observations of the dark asteroids (165) Loreley and (419) Aurelia are shown in Figure 3 and exhibit practically no opposition effect. Note the steeper slope of the strong backscattering effect for the darker objects, mainly due to the decreased multiple scattering. It is probable that the main contribution to the phase curves of (165) Loreley and (419) Aurelia comes from shadowing due to surface irregularities, which hints that, perhaps, no narrow–angle opposition effect can be expected from shadowing in the case of regoliths of atmosphereless bodies.

Objects exhibiting the opposition effect also exhibit negative polarization. Lyot (1929) discovered the negative polarization for Saturn's rings and reported it simultaneously with the linear polarization for the Moon. Since then, the polarization of Saturn's rings has been observed, for example, by Johnson et al. (1980). Further studies of the lunar polarization have been carried out by Dollfus and Bowell (1970), Shkuratov and Opanasenko (1992), and by Shkuratov et al. (1992). Asteroid polarization curves have been extensively observed by Zellner et al. (1974) and by Zellner and Gradie (1976).

Unfortunately, the polarizations of (165) Loreley and (419) Aurelia have not been recorded. It would be important to observe very dark asteroids and search for saturation of polarization, the stage where the negative polarization begins to disappear with decreasing single–particle albedo. It has already been found in laboratory experiments by Zellner et al. (1977) for mixtures of hydrated magnesian silicate and small particles of carbon black.

Qualitative interpretation of the opposition effects in Figure 3 can be carried out on the basis of the coherent backscattering mechanism. For the dark objects (165) Loreley and (419) Aurelia, the absence of a nonlinear brightening can be due to the absence of multiply scattered light. For the brighter Moon, a non–linear surge begins to show up and could be ascribed to increased multiple scattering. For the even brighter (44) Nysa and (64) Angelina, as for Saturn's rings, the amount of multiple scattering is considerable, causing a pronounced opposition effect. Furthermore, Europa is the brightest object in this sample and, in agreement with the coherent backscattering mechanism, exhibits the sharpest opposition effect.

The polarization observations also agree with the predictions of the coherent backscattering mechanism. The bright satellite Europa, asteroids (44) Nysa and (64) Angelina, and Saturn's rings have a weaker polarization because of increased proportion of unpolarized multiple scattering from orders higher than the second. Note that the theoretical calculations also support the idea that the negative polarization extends to larger phase angles for larger refractive indices.

By far the most significant dilemma in adopting the coherent backscattering explanation for the opposition phenomena is the often largely differing angular widths of the observed opposition effect and negative polarization. In that light, one can understand the backscattering phenomena of Europa and Saturn's rings as caused by coherent backscattering, but has difficulties in explaining the entire negative polarization ranges for the Moon, and the asteroids (44) Nysa and (64) Angelina (Figures 3 and 4). Further theoretical and experimental studies will have to be carried out to resolve whether coherent backscattering in multi–scale inhomogeneous media (including scattering from rough interfaces) could lead to such broad polarization effects.

3. Theories and Experiments

Here I review the theoretical and experimental work before the coherent backscattering era in studies of light scattering by solar system dust particles. Mutual shadowing was the generally accepted explanation for the opposition effect. It was the most popular explanation for the negative linear polarization, too, even without solid theoretical or experimental support. Partly because of that, numerous negative polarization models or mechanisms have appeared in the literature.

3. 1. INTENSITY

As mentioned before, the first steps in the interpretation of the opposition effect of Saturn's rings were taken by Seeliger (1887) on the basis of Müller's observations (1893). However, if one assumes the classical many–particle–thick ring model and that the opposition effect is related to mutual shadowing, the volume density (or volume fraction) for the ring particles would have to be much lower than predicted from ring dynamics studies (L. W. Esposito 1988, private communication). This is a serious contradiction between two different approaches to determining the volume density, as was emphasized by Irvine et al. (1988), who showed that a very small amount of trough retroreflecting particles in Saturn's rings would explain the opposition effect and relax the requirement of a many–particle–thick ring system. (Trough and corner retroreflection are second–order and third–order backward reflection from two and three perpendicular facets, respectively.) The same result would follow if the opposition effect could be addressed to coherent backscattering in individual ring particles.

Bobrov (1940) investigated the phase curve of Saturn's rings and later generalized Seeliger's shadowing calculations for particles of unequal size (1961). The theoretical considerations of Seeliger and Bobrov were reviewed by Irvine (1966), who also briefly analyzed the possible applications of the mutual shadowing calculations. Hämeen–Anttila and Vaaraniemi (1975) derived a photometric function for Saturn's rings assuming a monolayer ring model. Esposito (1979) extended the applicability of the classical shadowing calculations to higher particle volume densities by means of a van der Waals correction in the particle distribution function. He showed that the contribution from second–order shadowing is very small compared to the dominant first–order one. The most recent mutual shadowing calculations have been carried out by Shkuratov (1988a), Peltoniemi and Lumme (1992), and Peltoniemi (1993).

Hapke (1963) constructed a shadowing model for the lunar strong backscattering effect, preceded by photometric studies of complicated surfaces (Hapke and van Horn 1963). The lunar opposition effect was confirmed by Gehrels et al. (1964), and by van Diggelen (1964). Soon thereafter, Hapke (1966) extended his shadowing calculations to explain the lunar opposition effect, too. Since then, Hapke (1981) has been refining his theoretical calculations, treating light scattering by regoliths using radiative transfer equation. Theoretical work has been followed by experiments and interpretation of observations (Hapke and Wells 1981), and a correction for macroscopic roughness (Hapke 1984). In his relatively recent work (Hapke 1986), he still emphasized the opposition effect as being due to mutual shadowing.

Lumme (1971) derived a mutual shadowing model to minimize the restrictive assumptions of the earlier calculations, and found good agreement between observations and his theoretical considerations. Later, Lumme and Bowell (1981a) developed a radiative transfer model including new shadowing calculations and considerations of multiple scattering. The theoretical model was followed by an interpretation of phase curves (1981b), including the interpretation of the observed asteroid phase curves (e.g., Harris and Young 1989). The model was also applied to the lunar phase curve (Lumme and Irvine 1982). In connection to the Phobos space mission, Lumme et al. (1990) further developed their treatment of macroscopic surface roughness.

Heated discussion has sometimes taken place when the Hapke and Lumme–Bowell models have been compared to each other (Hapke 1982, Lumme and Bowell 1982). Both models have been criticized for unphysical parametrization. A recent review of the models is presented in Bowell et al. (1989).

Whitaker (1979) compared the phase relations of several asteroids, Mercury, and the Moon, and noted the similarity of the opposition effects. He expressed doubts concerning the mutual shadowing explanation. The first–order similarity for the opposition effect of asteroids was also noticed by Scaltriti and Zappalà (1980). They extracted the linear part of the phase curves (magnitude scale) and showed the similarity of the remaining nonlinear effects. However, they stated that the resulting rather similar nonlinear surges might have been due to the restricted range of geometric albedos in their sample of asteroids.

Opposition effect mechanisms other than mutual shadowing or coherent backscattering have been considered every now and then. The corner, trough and lense retroreflection mechanisms, which have their basis on the shape and structure of the dust particles, were summarized by Trowbridge (1978, 1984), and also analyzed by Akimov (1980).

Muinonen (1989a) and Muinonen et al. (1989) carried out investigations of internal corner and trough retroreflection from randomly oriented crystal–shaped particles. Strong backscattering peaks were confirmed when the particles contained facets precisely perpendicular to each other, but the peaks were rather sensitive to small changes from the rectangular forms. Adding the electromagnetic phase in the computations would produce coherent backscattering, and thus sharpen the backscattering peaks due to trough and corner retroreflection. However, the assumption of a sufficient number of specific geometries among the surface particles may be correct in some cases, but seems unlikely to be generally true. The same difficulty rises when trying to explain the observed opposition effects with the glory phenomenon of light scattered by spheres (e.g., Franklin and Cook 1965). (Note, however, that the glory phenomenon can be partly understood as coherent backscattering.)

3. 2. LINEAR POLARIZATION

For negative linear polarization, Öhman (1955) suggested that the negative polarization could be due to trough retroreflection. He was aware of the fact that these kinds of surface structures would also lead to an opposition effect. Although the lunar samples do not support the widespread occurrence of rectangular troughs in the dust particles, this mechanism has a sound physical basis, is worthy of an examination, and may occasionally contribute to the observed linear polarization. The trough retroreflection mechanism for polarization was studied further by Muinonen (1989a) and Muinonen et al. (1989) in the context of crystal scattering with a result parallel to that for the intensity : negative polarization appeared for rectangular crystal particles, but disappeared for non–rectangular shapes.

Hopfield (1966) pointed out that negative linear polarization could be explained by a Sommerfeld diffraction mechanism (Born and Wolf 1970) connected to mutual shadowing. Behind the edge of a thin half–plane of material with high electric conductivity, to be taken as an opaque dust particle, the scattered electromagnetic field is negatively polarized. According to Hopfield, this component would then be reflected from underlying structures and be registered by the observer. The requirement of a specific diffraction and reflection geometry and material of high electric conductivity restricts the applicability of this interpretation. Hopfield emphasized that it is natural to search for a common explanation of the opposition effect and negative polarization. Lumme et al. (1980) made laboratory experiments to investigate the mechanism but were not convinced of its relevance in the context of solar system observations.

McCoyd (1967) related the negative polarization to transmission and total internal reflection, in an assumed coating on the scattering dust particles. Being only one–dimensional, the model is limited, though it leads to correct qualitative results. Furthermore, the assumption of a coating seems to make this interpretation unrealistic for solar system objects. Lumme (1979) introduced an explanation based on transmission through transparent dust particles. Negative polarization is also observed for opaque materials, and thus cannot be fully explained with transmitted wave components.

Steigman (1978) suggested a model, where second–order reflection in flat–bottomed cylindrical pits results in negative polarization. Steigman's model is one of those models, in which the specific geometric requirements decrease the applicability. However, it indicates the ambiguity of the inversion problem : knowing only the linear polarization it is impossible to derive unambiguous information about the surface conditions.

Wolff (1975) presented a second–order reflection explanation based on a hypothesis of selective shadowing of negatively and positively polarized rays. No mathematically consistent theoretical verification of this mechanism has been presented, though it has undoubtedly been the most popular one. The mechanism has been experimentally verified only for non–isotropic surfaces covered with parallel grooves (Geake et al. 1984). The extension to realistic isotropic surfaces is far from obvious. However, Geake et al. concluded that second–order interactions are needed to produce negative polarization and that diffraction effects may play a significant role when small–scale surface textures are involved.

Gehrels (1977) supported Wolff's mechanism, and presented a geometric flat–bottomed pit model that, according to him, resulted in a net negative polarization near the backward direction. Muinonen et al. (1992) carried out some simple geometric calculations for shadowing by cylindrical pits and bumps of varying height–to–width ratios, and concluded that Wolff's mechanism was at least of an order of magnitude too weak to be significant.

Kolokolova (1990) offered complicated multiparameter geometric considerations for random rough surfaces that seemed to support Wolff's mechanism. In contrast, Kolokolova et al. (1993) analyzed the experiments by Geake and Geake (1990) and concluded that Wolff's mechanism could not explain the linear polarization of subwavelength particles but, rather, the coherent backscattering mechanism had to be invoked to explain the measurements.

Using Wolff's mechanism, Shkuratov (1982) and Shkuratov et al. (1988b) modeled negative polarization for particulate media and for opaque rough surfaces. Theoretical calculations by Peltoniemi et al. (1989) for stochastically rough particles and by Peltoniemi and Lumme (1992) for closely packed scattering media do not confirm a purely geometric explanation for the negative polarization. Moreover, theoretical studies of rough surface shadowing (Muinonen et al. 1990) show that, e.g., at normal incidence, a surface has to be extremely rough to eliminate the emergence of rays into small phase angles. The supporters of Wolff's shadowing mechanism are invited to present solid theoretical and experimental evidence for the mechanism—currently, no such evidence is available in the literature.

Lumme and Bowell (1985) studied light scattering by interplanetary dust, and derived the single particle phase functions for the parallel and perpendicular polarizations. Comparing these phase functions with the observations of planetary regoliths, they then concluded that the linear polarization of the interplanetary dust particles strongly resembled that of the typical regolith particles. Light scattering by cometary dust (e.g., Levasseur–Regourd et al. 1993) further adds to the complementary set of scattering problems in the solar system.

3. 3. LABORATORY MEASUREMENTS

Oetking's (1966) laboratory experiments indicated that most terrestrial substances, including standard diffusing surfaces, showed a prominent rise in reflectivity near the backscattering direction. He verified, for example, that fine micron–sized particles of aluminum oxide developed much higher backscattering peaks than coarser particles of the same material. Extensive experimental polarization studies of simulated lunar surfaces have been carried out by Egan (1967), Dollfus et al. (1971), Dollfus and Titulaer (1971), and by Bowell et al. (1972), who include particularly good documentation of the measured samples.

4. Coherent Backscattering Mechanism

It is useful to summarize the present state of research in the field of electromagnetic scattering by random media. There are several reasons why the existing theoretical treatments are not directly applicable to light scattering by solar system dust particles. The dust particles, though plausibly exhibiting wavelength–sized irregularities, are themselves thought to be very large compared to the wavelength. Also, there are dust particles of various materials in regoliths, and the particles themselves can be inhomogeneous aggregates. The regolith dust is probably closely packed with a volume density about 40%. Thus solar system regoliths are multi–scale inhomogeneous random media with strongly fluctuating electromagnetic conditions (i.e., having strong contrasts in the electric permittivity).

Coherent backscattering has been studied mainly for two kinds of scattering media : rough surfaces that are interfaces of two electromagnetically homogeneous media; and volumes of discrete randomly distributed scatterers. At the moment, both lines of research are relevant for light scattering by solar system dust particles. In particular, there has been recent activity in studies of rough surface scattering, which can be partly understood by the very fundamental nature of rough interfaces in all scattering problems.

In addition to coherent backscattering by rough surfaces and volumes of particles, there is coherent backscattering by single particles, which, excluding Mie scattering for a moment, has not been much studied. Such backscattering is of utmost relevance in the solar system context, where the irregular particles are mostly much larger than the wavelength of light. The single particles can sometimes be taken as clusters of subparticles; the wavelength–sized or smaller subparticles are probably not uniformly distributed, for example, in planetary regoliths. Ultimately, one needs to take ensemble averages (e.g., orientation averages) of individual particles and thus approaches the volume scattering problem. The basic mechanism itself can nevertheless be due to the single particles themselves, and not due to the interactions between these particles.

There are nomenclature problems when one discusses radiative transfer and electromagnetic theories in the same context. Examples of such difficulties are "homogeneous media" and "rough surfaces". The reader is urged to consult the literature to overcome possible nomenclature problems.

4. 1. ROUGH SURFACES

The profound experiments by O'Donnell and Mendez (1987) confirmed the existence of the backward enhancement for random rough surfaces. They also measured negative linear polarization, although they used different terminology and were not familiar with the observations of solar system dust particles. They noticed that, for normal incidence on an isotropic surface, the secondary maxima near the backward direction behaved differently in the planes parallel and perpendicular to the electric vector of the incident field. Experiments have also been carried out by Gu et al. (1989). They compared the results with the theory by McGurn et al. (1985) and by Celli et al. (1985), which stated that, in certain conditions, the backward enhancement can be related to the localization of surface polaritons by the random surface roughness. The measured backscattering enhancement exceeded the theoretical predictions.

Theoretical studies of scattering by random rough surfaces were further carried out by Bahar and Fitzwater (1989) and by Soto–Crespo and Nieto–Vesperinas (1989). Bahar and Fitzwater related the backward enhancement to first–order scattering and, on the other hand, Michel et al. (1989) showed that the phenomenon rose from multiple scattering. The approaches by Soto–Crespo and Nieto–Vesperinas and by Michel et al. are restricted to one–dimensional random rough surfaces.

Ishimaru (1990) pointed out that two different enhancement phenomena are mainly observed for rough surfaces. The enhancement seems to occur both for large heights and steep slopes, and also for small height variations. The latter can be understood with the help of surface wave modes, but the former needs more examination. Enhanced backscattering through a deep random phase screen has been investigated by Jakeman (1988) and by Tapster et al. (1989). The book edited by Nieto–Vesperinas and Dainty (1990) summarizes open questions of electromagnetic scattering in volumes and surfaces.

Investigations of rough surface backscattering have been continued by, e.g., Kim et al. (1990), Soto–Grespo et al. (1990), and Bruce and Dainty (1991ab). McGurn (1990) provides a review of rough surface scattering with an emphasis on Anderson localization of surface polaritons.

4. 2. SINGLE PARTICLES

A fact that has been almost ignored in recent studies of coherent backscattering is the coherent nature of backscattering by spherical particles (van de Hulst 1957). van de Hulst treats scattering by spheres in the geometric optics approximation, including the electromagnetic phase, thus accounting for coherent backscattering. In general, it is impossible to distinguish strictly between single particles and aggregates of single particles, and thus some many–particle calculations are reviewed in this section.

How do irregular single particles exhibit coherent backscattering? The mechanism of cyclic passage of waves inside an individual scatterer and the subsequent coherent backscattering is indicated for an arbitrary particle by Muinonen (1989a), when introducing the Kirchhoff approximation (and its modified version) for light scattering by single particles. Preliminary results for tetrahedral crystals in the full Kirchhoff approximation (Muinonen 1991) showed weak signs of coherent backscattering in both intensity and polarization.

The simplest possible electromagnetic scattering problem of two particles is that of two dipole (or Rayleigh) particles, and was solved analytically by Muinonen (1989b). The negative linear polarization was verified to accompany the backscattering enhancement in second–order scattering, and the qualitative explanation for the coherent backscattering mechanism for the negative polarization was given. However, due to the small scattering cross section, the coherent second–order backscattering peak and negative polarization do not show up in total angular scattering in the validity region of the electric dipole approximation.

Lindell et al. (1991) and Muinonen et al. (1991) considered scattering by small objects close to an interface using the Exact Image Theory formulation. A generalized Green function was derived to account for the interface close to the scattering particle, assumed to be small compared to the wavelength. Intuitively, it is clear that the multiple scattering contributions increase when the second single dipole scatterer in Muinonen (1989b) is replaced with a dielectric half–space. Indeed, the co–existence of the negative polarization and the backscattering enhancement in the total diffuse scattered field component are confirmed through simulations of a rough surface covered with dipolar inhomogeneities (Figure 2). This averaging is only a rough approach to simulate natural conditions, and is not to be understood as a model for solar system observations. In further verifications, the first–order Fresnel reflection component should also be taken into account.

Muinonen and Lumme (1991) showed results for coherent backscattering from two spherically curved surface elements, and demonstrated how the backscattering peak and negative polarization vanished when the electromagnetic phase was excluded from the calculations. In general, the calculations by Muinonen et al. can be criticized for not being readily applicable to the interpretation of solar system observations.

Lumme and Rahola (1994; see also Hage 1991) computed scattering by porous single particles using an improved numerical method for the discrete–dipole approximation by Purcell and Pennypacker (1973). In searching for coherent backscattering phenomena, they could not conclude whether they saw backscattering enhancement or negative linear polarization caused by coherent backscattering. Since the discrete–dipole approximation is well suited for studies of interference phenomena, I encourage the continuation of search efforts.

4. 3. VOLUMES OF PARTICLES

Pre–1982 backscattering enhancement studies have been well reviewed by Kravtsov and Saichev (1982). They discussed the fluctuation effects in double passage of waves propagating through the same inhomogeneities of a random medium, touching also the topic of coherent backscattering. The mechanism of coherent backscattering was presented by Watson (1969), who studied multiple scattering of electromagnetic waves in an extended underdense plasma. Watson emphasized that for calculating radar backscattering, the coherence of multiply scattering waves propagating in opposite directions had to be taken into account. de Wolf (1971) brought up the phenomenon in his treatment of electromagnetic scattering by an extended dielectric turbulent medium.

The coherent backscattering phenomenon has been experimentally verified in controlled light scattering measurements for densely distributed latex and polystyrene microspheres by Kuga and Ishimaru (1984), van Albada and Lagendijk (1985), and by Wolf and Maret (1985). In these experiments, the widths of the backscattering peaks were less than 1°. After these verifications, the interest in the phenomenon has increased rapidly in the field of electromagnetic scattering. van Albada and Lagendijk, and Wolf and Maret investigated the coherent backscattering phenomenon in connection to weak localization of photons in disordered dielectric media. This field of research is reviewed by MacKintosh and John (1988), and by McGurn (1990).

Tsang and Ishimaru (1984, 1985) interpreted the measurements on the basis of the so–called diffusion approximation. They used a scalar diagrammatic theory for randomly distributed, isotropically scattering point–like particles, and found that the angular width of the peak was related to the transport length in the medium. Also, they concluded that multiple scattering contributions from orders higher than the second play an important role in the peak formation. Although this approach clarifies the essential physics in coherent backscattering, the analysis can be criticized for its scalar nature, and for the non-realistic assumption of isotropic single scattering. The latter assumption appears analogous to Chandrasekhar's work on radiative transfer (1960). Later, the approach was extended to non-isotropic scatterers (Ishimaru and Tsang 1988).

Ma et al. (1988) treated electromagnetic scattering by discrete random medium in a distorted Born approximation using transition-matrix (T-matrix) formalism, and emphasized that the scatterers in the aforementioned experiments were large or comparable to the wavelength, a fact which should be taken into account. The formalism enabled the consideration of the size and orientation distributions and physical properties of the scatterers (Varadan et al. 1983, Varadan et al. 1987). They interpreted the measurements by van Albada and Lagendijk (1985) and indicated the CPU time problems encountered in the numerical analysis. Also, they brought up the fundamental question of whether the applied pair statistics satisfactorily approximate the real higher order statistics in a discrete random medium.

Bahar and Fitzwater (1988) studied the backscattering enhancement from random distributions of finitely conducting spherical and random rough particles using radiative transfer equation and the so-called full-wave approach. In their treatise on random medium, they related the backward enhancement to single scattering from either smooth or rough spheres. Evidently, the full-wave approach leads to interesting results.

The coherent backscattering mechanism has been recently investigated by Shkuratov (1988b, 1989), Shkuratov et al. (1989), and Shkuratov and Muinonen (1991) using both scalar and vector formulations of radiative transfer and including the electromagnetic phase. One of their goals has been to derive simple formulae describing the main features of the observations and experiments. However, they can be criticized for just this philosophy : over-simplification may yield misleading results.

Coherent backscattering was invoked to explain the unusual radar characteristics of outer planet satellites by Hapke (1990). Hapke et al. (1993) carried out a circular polarization experiment to verify whether the lunar opposition effect was caused by shadow-hiding or coherent backscattering. They studied the linear polarization and circular polarization ratios, defined as the ratios of the intensity scattered with the sense of polarization not expected upon reflection from a smooth surface to the intensity scattered with the sense that would be expected. They noticed that the linear polarization ratio decreased as the circular polarization ratio increased for the lunar samples toward the backward direction or opposition. They then stated that the experiment provided "unequivocal proof" that coherent backscattering was dominating the opposition effects for the measured samples. However, the lack of quantitative theoretical interpretation of their laboratory results renders their proof speculative. Their experimental results do hint strongly at a multiple scattering explanation for the opposition phenomena, but the results await a quantitative theoretical explanation just as the lunar opposition effect and negative polarization.

Mishchenko and Dlugach (1991) analyzed the amplitude of the coherent backscattering peak using a vector multiple-scattering theory. They assumed that the enhancement was an exact multiple of two compared to the radiative transfer contribution from scattering orders higher than the first. The amplitude of the opposition effect was then defined as the ratio of the total coherent and incoherent scattering to the total incoherent scattering. The amplitude for the opposition effect varied from about 1.3 to about 1.6, resembling the opposition effects of solar system objects.

The copolarized and depolarized backscattering enhancement factors were studied by Mishchenko (1991) for Rayleigh scatterers and spherical latex particles in water. Mishchenko does not calculate the angular dependence of the coherent backscattering peak but assumes the shape of the peak from other contexts (e.g., Ozrin 1992ab). This "shortcut" is a deficiency in his otherwise thorough work that derives from radiative transfer theory through the aforementioned assumption of the amplitude of the coherent backscattering peak.

Mishchenko and Dlugach (1992) studied the opposition effect of Saturn's rings in the context of coherent backscattering. Mishchenko (1993) then studied the negative linear polarization of Saturn's rings, and concluded that coherent backscattering cannot explain the entire range of negative polarization, but rather, mechanisms such as Wolff's shadowing mechanism (Wolff 1975) had to be incorporated.

Mishchenko and Dlugach (1993) studied the coherent backscattering mechanism for the E–type asteroids (44) Nysa and (64) Angelina (see also Shkuratov and Muinonen 1991), and gave a brief review of the present status of coherent backscattering studies. Kolokolova et al. (1993) supported Wolff's mechanism as a general explanation for the negative polarization, but stated that the coherent backscattering mechanism needed to be introduced to explain the negative polarization of samples of subwavelength–sized particles.

Peters (1992) has proposed a vector formulation accounting for polarization and absorption effects and small or large scatterers. His work is a generalization of the studies by MacKintosh and John (1988). However, Peters was bound to introduce approximations that were later criticized by Mishchenko and Dlugach (1993), and the validity of the approximations still need to be verified via more thorough theoretical and experimental work.

Ozrin (1992ab) developed a vector formulation for coherent backscattering by samples of Rayleigh scatterers. He considered a semi–infinite random medium composed of nonabsorbing point–like scatterers. For normally incident linearly polarized light, he found the angular distribution of the backward scattered intensity. However, the deficiency in Ozrin's work was his assumption that the diffuse background radiation was independent of the phase angle near the backward direction.

Recently, Shkuratov et al. reported strong negative polarization for samples that they considered relevant for the interpretation of the solar system observations (Shkuratov and Akimov 1987; Shkuratov et al. 1987, 1988a). Furthermore, Shkuratov and Opanasenko (1992) and Shkuratov et al. (1992) reported studies of the lunar negative and positive polarization, accompanied by supporting laboratory simulations. I am currently involved in designing and constructing a new scatterometer for experiments, in particular, close to the backscattering direction (Piironen and Muinonen 1993).

5. Discussion

Unambiguous quantitative inversions of solar system scattering problems are usually not possible, which is evident from the fact that many of the mechanisms for the opposition effect or negative polarization described above could work in special cases. However, the inversion problems can be approached through an analysis that attempts to make as few assumptions as possible. Adopting this approach for the backscattering studies, we should concentrate our research on the coherent backscattering mechanism and, further, on its relation to mutual shadowing.

Many theoretical aspects of the coherent backscattering phenomenon are still not well understood. For example, the coherent internal backscattering by single particles cannot be omitted in the case of bright materials. This could be investigated by treating the scattering by stochastically rough particles in the Kirchhoff approximation. Examinations of second–order external reflection from random rough surfaces should be continued, which would give further insight, especially, into the origin of the negative polarization.

The Exact Image Theory (e.g., Lindell et al. 1991) can also be applied to scatterers that are not necessarily small compared to the wavelength. The main advantage of the method is that it uses the already existing solutions for isolated objects. The possible inhomogeneity of the individual dust particles could be taken into account, perhaps, by applying the Exact Image Theory to scatterers that are inhomogeneities of an otherwise homogeneous half–space medium. These kinds of studies are needed in the investigation of light scattering by solar system dust particles, since it is not well understood where the main contributions to coherent backscattering come from. Investigations could also be continued by analyzing a three–particle scattering problem in the electric dipole approximation. This would give insight into the intensity and polarization effects in third–order scattering. These solutions could also be important for further improvements of the discrete–dipole approximation (e.g., Lumme and Rahola 1994).

Future laboratory experiments should first be concentrated on controlled measurements in which all the relevant parameters of the rough or particulate surface are known. For example, in the case of rough surfaces, detailed knowledge of the surface height statistics is necessary for theoretical treatments. Unfortunately, a part of the laboratory work in the past must be classified as pure laboratory observations rather than as controlled experiments. It is the intelligent synthesis of theory and experiments that finally leads us to understand the opposition effect and negative linear polarization.

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