Light scattering by dust particles in the solar system with assessments of both direct and inverse problems

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We analyze both the intensity and linear polarization of cosmic dust particles by using the physically exact fixed cluster *T*-matrix method for aggregates of spheres and DDA for aggregates of Gaussian random spheres. We study both the spherical geometry (in cometary comae) and cylindrical slabs (for regoliths) up to 1024 monomers with size parameters less than ~3. It is straightforward to produce the observed linear polarization in both geometries while the typically convex opposition spike seems to require the regolith geometry.

INTRODUCTION

The nonlinear brightening and linear polarization, particularly the negative branch, close to the opposition geometry of a large number of atmosphereless bodies in the solar system are issues which have been known for decades. The quantitative explanation with measurable physical parameters is lacking to a rather large extent. The coherent backscattering (CB) mechanism seems to be the leading factor at small phase angles α, because CB simultaneously explains both the increase of the brightness and the negative branch. However, the actual shape of the brightness increase still needs some clarification. In most cases the observed shape is convex (second derivative positive at α=0°, while almost all the existing computations of CB with various aggregate parameters produce concave shapes.

Often some adjustable parameters that produce nice formal fits to the data are assumed without any real physical meaning. These solutions are rarely unique. Because of the complexity of the problem the real inversion at this point seems rather hopeless. We can, however, find reasonable constraints for some of the key parameters.

AGGREGATE GEOMETRIES

We assume for all the aggregates that every monomer has a touching neighbor. This does not need to be actually true because some electrostatic forces can produce some separation. Our computations show that if the separation is less than about 10% of the radii the results are fairly insensitive to this. The key parameters in our aggregates are: the size and size distribution of the monomers, the particle packing algorithm and the packing density *pD*. The best source to evaluate some of these are several images of the cosmic dust particles (CDP) on the internet with the accurate scale bars. From these images we have been able to conclude that the monomers are rather round. The radii r seem to lay in the interval from 0.08 μm to 0.22

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μm and the size distribution is rather close to a lognormal distribution. Naturally we must take this information with a special caution if applied to the whole population of the CDPs.

We first consider packing of spheres with an arbitrary size distribution. A popular packing code for aggregates is either the ballistic particle-cluster aggregation (PC) or the ballistic cluster-cluster aggregation (CC). The PC code produces aggregates with roughly the same *pD*. The other code we have used randomly selects a monomer from a binomial distribution. Here we insert a new one as a touching neighbor if it does not intersect the others. With one parameter we can create quite different *pD*s. To estimate quantitatively *pD* we need a reference volume. This volume is often taken as a sphere with a minimum radius that confines all the packed monomers. This is not a good choice because it underestimates *pD* for elongated aggregates. Instead, we use the convex hull (CH) for which ready codes exist on the internet.

For nonspherical monomers we can pack general ellipsoids, standard and spherocylinders, Gaussian random spheres (GRS) and convex polyhedra. For these monomers the parameter space increases considerably and systematical light-scattering studies have to wait.

LIGHT SCATTERING METHODS

There are two widely used methods to do light scattering of aggregates. First, the superposition *T* matrix (CTM) [1] and, second, some of the several versions of the discrete dipole approximation (DDA) [2] are used. The original CTM uses an analytical orientation averaging but as recently shown [3], the fixed orientation technique (FCTM) deserves some obvious benefits over the standard CTM. Particularly, with this version, the number of monomers can be greatly increased. A highly efficient numerical integration technique which suits both the CTM and the DDA methods, called *cubature,* was recently found by Penttilä [4].

Both CTM and DDA have their pros and cons. If very accurate results are required close to the backscattering then the CTM method is superior. If the monomer shape is of key importance then, of course, the DDA method is the only possibility. Also, if we are interested in a large number *n* of rather small spherical monomers, then DDA is the only choice.

LIGHT SCATTERING BY COMETARY DUST

The cometary dust particles have been modeled by PC and CC aggregates. The number of free parameters even with some simplifying assumptions is so large that a unique inversion of the good observational polarization data in the interval $0^o<\alpha<120^o$ is quite impossible.

We have scanned the realistic range of the real part m_R of the refractive index in the range from 1.5 to 1.8. The imaginary part m_I seems to have a small effect if it is less than about 0.01. Only as an exercise, we have studied two models based on the PC and CC geometries (Fig. 1). In the former we assume a collection of aggregates of 256 equal-sized monomers and numerically integrate the results in the range $0.75<x<2.5$ where x is the size parameter and follows a power law with one parameter γ. Assuming m_I =0.01 leaves only γ and m_R to be solved. A very extensive data collection for cometary polarization is provided with the *Database of comet polarimetry*[*]. Of these the data in the red filter is most extensive and can be used to obtain the two free parameters. We can see that the fit is very good indeed and the free parameters come out as m_R=1.68 and γ=2.73. The same kind of fits can also be done to the data in different colors.

The other case we studied is a CC aggregate (Fig. 1). We assumed 16 sub-clusters with 32 equal-sized monomers in each. The 16 values for the radii were taken randomly from a power law in the same range as above. We used eight realizations and took the mean of those. This model leaves only one parameter, m_R, to be determined for which we got 1.63. The fit is also very good. These exercises clearly indicate how difficult it is to obtain unique solutions.

To see the effect of nonsphericity on the results we have packed 128 lognormally distributed monomer GRSs with our code and used DDA with the cubature orientation averaging to compute an example. In Fig. 2 we compare these results to those of a PC aggregate with spherical monomers. We assumed here that m_R =1.6, m_I =0.01.

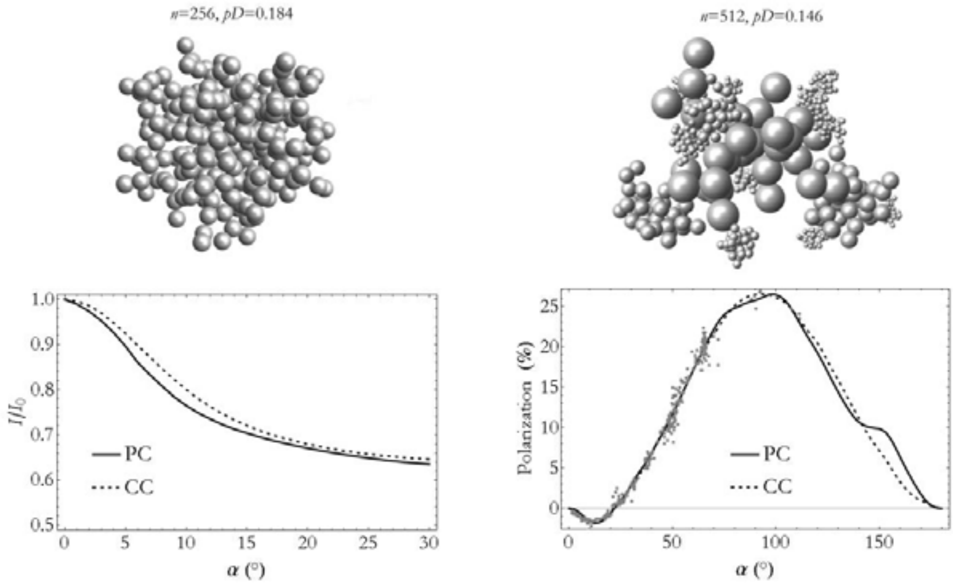

Figure 1. Intensities and polarizations are computed of PC (top left) and CC (top right) aggregates and compared to the red filter data of cometary polarization. For details, see text.

LIGHT SCATTERING BY REGOLITHS

With current methods it is impossible to model the horizontally very large regoliths. We do this approximately by using cylindrical slabs with the size parameter radius R_x>>1 using FCTM in the range 0°<α<20°. One of our exercises is shown in Fig. 3. We integrate the computations over the angle of incidence *i* in the range 0°<*i*<20°. Comparison to a PC aggregate with equal constituents shows that the intensity spike is stronger for the slab, al-

[*] Available on the internet at the Small Bodies Node (http://sbn.pds.nasa.gov/).

though not yet clearly convex as required by observed data. The linear polarization is more asymmetric than those of the PC results.

With DDA code ADDA it is possible to analyze slabs up to R_x ~100 and height H_x ~20 which we will do in near future. We think that the regolith structure could best be described as random heterogeneous medium in submicron scale where CB is mainly responsible for the intensity and polarization behavior at the small phase angle observations. The sub millimeter scale can still cause some effects due to the mutual shadowing and surface roughness.

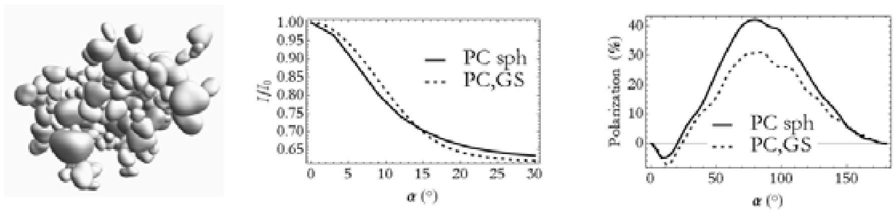

Figure 2. Normalized intensities and linear polarization are shown for PC aggregates of log-normally distributed spherical 128 monomers (not shown) and Gaussian spheres (GS).

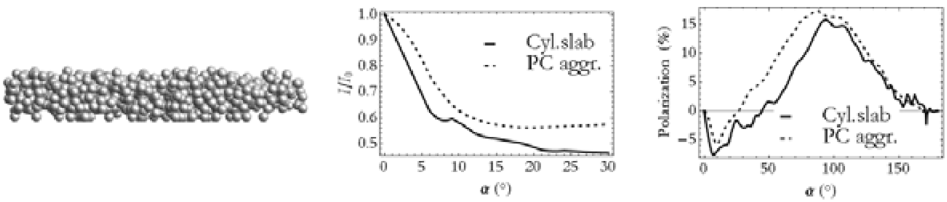

Figure 3. Normalized intensities and linear polarization for a PC aggregate and an extended cylindrical slab to model a regolith. In both cases we have equal sized monomers of x=1.75 and m=1.6+ i 0.001. The radius (in size parameters) of the slab is 53 and the height 20. Note particularly a stronger opposition spike and more asymmetric negative polarization.

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