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SCATTERING PROPERTIES OF DUST IN PLANET-FORMING DISKS: FIRST RESULTS FROM A MICROWAVE ANALOGY EXPERIMENT

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Abstract.
The agglomeration process of dust in protoplanetary disks is a key element to understand the formation of planets. However, important information is still missing, e.g., the shape, structure and composition of the dust. Several ways to study the properties of these dust exist: observations, numerical simulations, and laboratory measurements. This paper is focused on laboratory measurements and simulations using the the microwave analogy. The phase function and degree of linear polarization of fractal-like aggregates and particles with rough surfaces are studied. Measurements and simulations show that each type of analogs has its own typical scattering properties. Future work will be focused on two more detailed studies of fractal-like aggregates and rough surfaces.

Keywords: microwave analogy, scattering properties, phase function, degree of linear polarization, analogs, rough surfaces, fractal-like aggregates, protoplanetary dust.

1 Introduction

The microwave analogy is a well-known method relying on the Scale Invariance Rule (SIR) that has been used to measure the scattering properties of objects that would otherwise be difficult to manipulate individually (Greenberg et al. 1961). The SIR states that the scattering properties of analog particles measured at a different wavelength are equivalent to those of the original particles of the same shape, as long as the refractive index and the size-to-wavelength ratio (or size parameter: $X = 2\pi r/\lambda$) are conserved.

The present work uses the SIR and the micro-wave analogy experiment at Institut Fresnel in Marseille to study the scattering properties of analogs of dust found in the Solar System and in planet-forming disks, the ultimate goal being to provide direct observational constraints on the first phases of planet assembly, when tiny solid particles start to grow and form larger bodies. Different studies have suggested that aggregates and particles with rough surfaces can be found in different astronomical environments like comets (Güttler et al. 2019) , debris disks (Milli et al. 2017), and protoplanetary disks (Min et al. 2016). However, the only way to directly measure the dust in these disks is through observations and analysis of the scattered light. For this reason the proper characterisation of the scattering properties of different type of particles is of utmost importance. This is the goal of the present study.

To reach this goal we have considered two types of analogs: fractal-like aggregates (aggregates with a finite number of monomers) and compact particles with rough surfaces (Renard et al. 2021). These analogs were produced by additive manufacturing where the possibility to control their shape, structure, and refractive index is unique, and a definite advantage over other measurement laboratory methods. In this paper, we summarize our first results on these protoplanetary dust analogs. We detail how they are produced, what the measurement conditions are, and the scattering results. In particular, the Intensity phase function and degree of linear polarization are presented, i.e., the elements S11 and -S12/S11 of the Mueller matrix, respectively. These measurements are compared to our numerical model (Voznyuk et al. 2015) to validate the method and highlight their distinctive features. The ultimate goal is to retrieve the particles' properties like the surface roughness, fractal dimension (D_f), porosity and others. These results are the first laboratory measurements of protoplanetary dust disks analogs with controlled structures using the microwave analogy.

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2 Analogs

Two types of analogs were produced: fractal aggregates and compact particles with rough surfaces. To produce these analogs, a computer-aided design is followed by 3D printing. Virtual generation of fractal aggregates was based on the Diffusion Limited Aggregation software (DLA) developed by Wozniak et al. (2012). This software uses a particle-cluster aggregation scheme. All our aggregates are made of 74 monomers, each with a radius of 2.75 mm (overlapping of 10% between monomers), and a fractal prefactor of $k_0 = 1.593$. Five different fractal dimensions were printed $D_f = 2.8$, 2.5, 2.0, 1.7 and 1.5 with radius of gyration of 9.83 mm, 11.60 mm, 17.03 mm, 23.92 mm and 32.30 mm, respectively. Particles with rough surfaces were created from spheres of diameter 32.35 mm with a surface meshed with triangles. The distance between the center of the sphere and the vertex of each triangle were randomly modified to create the surface roughness. In total, five different surfaces were made with different levels of roughness.

Then, both types of analogs were printed using an additive manufacturing process named stereolithography (SLA). SLA works using a liquid acrylic resin that is photo-polymerized layer by layer by a UV laser. The resin used to print aggregates and rough surfaces had a refractive index of $1.7 + i0.03i$ (for more information see Renard et al. (2021)).

3 Measurement setup

Microwave analog measurements were performed in Marseille in the anechoic chamber of "Centre Commun de Ressources en Micro-Ondes". Wavelengths between 100mm and 16 mm (corresponding to frequencies of 3 GHz to 18 GHz) were used to measure all analogs. Emitter and receiver antennas worked at the same states of polarization, horizontal and then vertical; mixing these two polarizations non-polarised incident waves were obtained. The configuration that was used during measurements was a forward type configuration which corresponded to scattering angles (θ) from 0° to 130° (for more information see Geffrin et al. (2012)).

4 Results

The phase function S_{11} and the degree of linear polarization $-S_{12}/S_{11}$ were studied for both types of analogs. Measurements and finite element (FEM) simulations were compared for 16 different wavelengths from 100 to 16 mm. Here we present only four wavelengths: 60, 30, 20 and 16.7 mm.

For the fractal-like aggregates, results for the lowest, $D_f = 1.5$, and largest, $D_f = 2.8$, fractal dimensions are presented. They correspond to particles with an intermediate size parameter of $X_{int} = 6.77$ and $X_{int} = 2.06$, calculated with the radius of gyration of each aggregate at $\lambda = 30$ mm. The comparison of the scattering properties of the five fractal analogs will be published in Tobon Valencia et al. (2021).

The phase functions are illustrated in figure 1. Measurements and FEM simulations have the same behavior and amplitude levels. The difference between the phase function of the smallest and biggest fractal dimension is the number of lobes in the curves. For $D_f = 1.5$ there is one lobe while for $D_f = 2.8$ there are up to four lobes. In terms of the degree of linear polarization, shown in figure 2, there is also a difference between these two like-fractal aggregates. For $D_f = 1.5$ all four wavelengths have a Rayleigh-like behavior while for $D_f = 2.8$ the Rayleigh behavior is only present at $\lambda = 60$mm; the other three wavelengths have an oscillating behavior.

For the five particles with rough surfaces, only the roughest and smoothest ones are presented here. They also have an intermediate size parameter of $X_{int} = 3.4$. The full analysis of all particles will be published later. As can be seen in figure 3 the phase function of these two surfaces produce similar measurements of S_{11}. However, significant differences can be seen in $-S_{12}/S_{11}$, the linear polarisation. Figure 4 presents the differences between the degree of linear polarization of these two surfaces. The $-S_{12}/S_{11}$ parameter of the least rough surface has a more important amplitude of oscillation at all the scattering angles, compared to the roughest surface.

5 Conclusions

Simulations are in good agreement with measurements of phase functions and degrees of linear polarization for all four analogs, providing a cross-validation of these results. There are evident differences between aggregates of different fractal dimensions in both scattering properties: S_{11} and $-S_{12}/S_{11}$. In terms of rough surfaces, the degree of linear polarization is the scattering property with the most differences. In summary, the four analogs

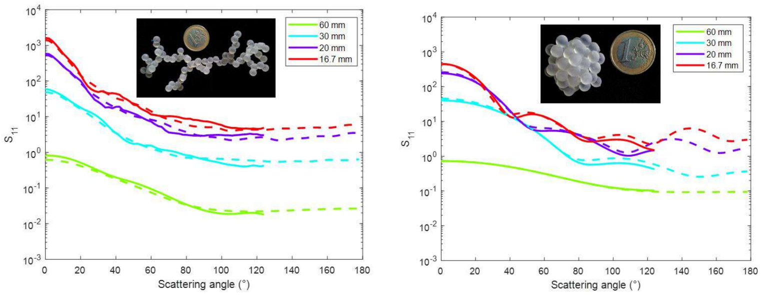

Fig. 1. Phase function of fractal-like aggregates for measurements (plain lines) and simulations (dashed line) at four different colours representing the wavelengths. **Left:** $D_f = 1.5$. **Right:** $D_f = 2.8$.

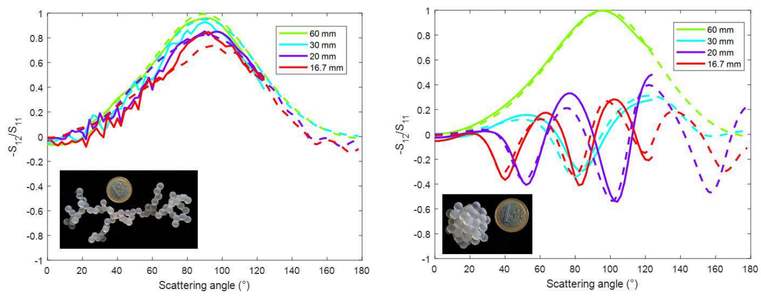

Fig. 2. Degree of linear polarization of fractal-like aggregates for measurements (plain lines) and simulations (dashed line) at four different colours representing the wavelengths. **Left:** $D_f = 1.5$. **Right:** $D_f = 2.8$.

studied here have different signatures. This is of essential importance for future comparisons of our analogs with protoplanetary dust.

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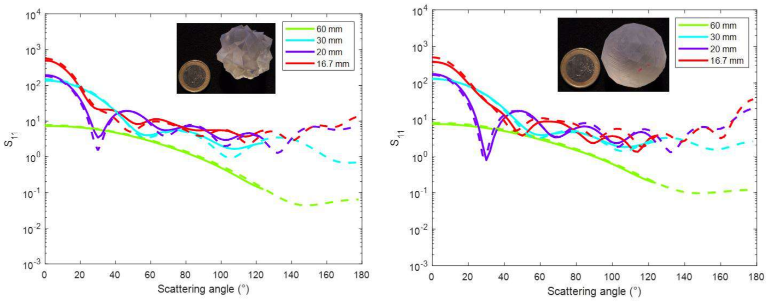

Fig. 3. Phase function of rough surfaces for measurements (full lines) and simulations (dashed line) at four different colours representing the wavelengths. **Left:** the roughest surface. **Right:** the smoothest surface.

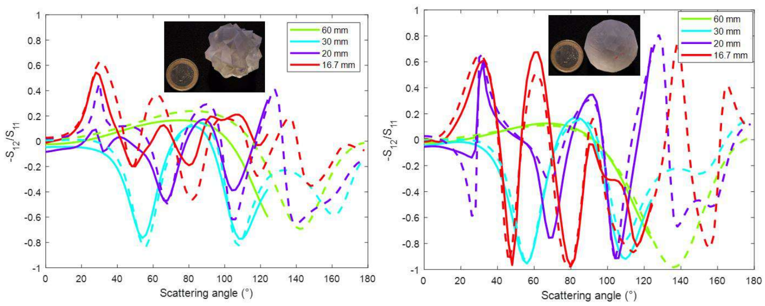

Fig. 4. Degree of linear polarization of rough surfaces for measurements (full lines) and simulations (dashed line) at four different colours representing the wavelengths. **Left:** the most rough surface. **Right:** the least rough surface.

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