3D-Printed Dust Analogs for Protoplanetary Disk Studies

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Astrophysical Context: Small dust particles in planet-forming circumstellar disks must grow by several orders of magnitude to form planetary embryos. The exact processes by which this happens remain unclear today. Information is known about the dust sizes and their rough chemical composition in disks, as measured via, e.g., spectral energy distribution measurements and fitting and near- and mid-infrared spectroscopy. However, particle shapes also hold important clues to the elusive dust-growth mechanisms, a better understanding of which is needed to advance our knowledge of the first stages of planet formation. Although rarely studied, particle shapes can be investigated via high resolution imaging of disks and the measurements of scattering phase functions in intensity and linear polarisation, from the optical to the millimeter wavelength range. To reveal the meaning of these phase functions, a comparison is necessary with a database of "measured" or "calculated" scattering properties of complex dust particles of known shapes, sizes, and composition. I will present our recent efforts to measure such scattering properties of complex dust particles from Laboratory Experiments.

Microwave analogy and additive manufacturing: Taking profit of the recent improvements of 3D printers, we built cm-sized analogs of small circumstellar dust particles with a variety of complex shapes and refractive index. The shapes include fractal aggregates with fractal dimensions, Df , in the range 1.5-2.8, particles with rough surfaces, CAI inclusions and chondrules from meteorites, random Gaussian spheres, etc... See Figure 1. The scattering properties of these analogs were measured in the frequency range 3-18 GHz (size parameters in the range 0.5-35) to mimic their behavior in the visible and/or millimeter range [1,2]. The refractive indices of various printing materials were measured and carefully selected to mimic the properties of relevant astronomical silicates and carbonaceous compounds at near-infrared and mm wavelengths.

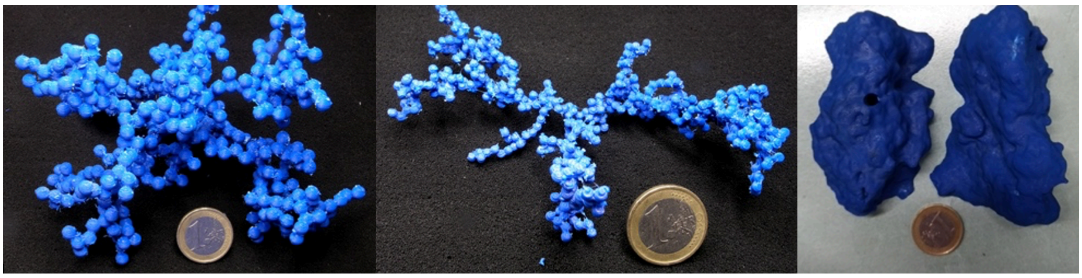

Figure 1: Printed analogs: (left) Fractal aggregate with 500 monomers, Df = 2.0. (Middle) Fractal aggregate with 500 monomers, Df = 1,7. (Right) Copy of a Calcium-Aluminum Rich inclusion. Exact geometry obtained via X-ray tomography. Real size of CAI inclusion = 0.77mm.

Results: The measurement protocol is described in [3, 4] who presented results for small fractal aggregates and rough spheres. New measurements are available for larger aggregates, Random Gaussian Spheres, and aggregates made of irregular monomers recently printed. Their relevance to understand the evolution of dust in protoplanetary disks will be discussed.

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References: [1] Saleh et al, IEEE Transactions on Antennas and Propagation, Volume 69, Issue 2, February (2021); [2] Vaillon and Geffrin, Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. 146, Oct. (2014); [3] Tobon-Valencia et al., Astronomy & Astrophysics, 666, A68 (2022); [4]Tobon-Valencia et al., Astronomy & Astrophysics, 688, A70 (2024)