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Dynamical evolution of cometary dust and its effect on polarization

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Abstract

Cometary dust will, when ejected from the nucleus, obtain significant angular velocities. In this work, we study the dynamical response of small, of wavelength-scale, irregular silicate particle monomers and a dimer under Sun-like illumination. As preliminary results under these conditions we found that the spin-up time scale to angular velocities that can destroy weakly bound aggregates is of the order of days.

1. Introduction

In a historic campaign, the European Space Agency (ESA) sent the Rosetta spacecraft to study the properties of the comet 67P/Churyumov-Gerasimenko. This marked the first occasion that *in-situ* measurements of comets were possible in addition to remote observations. Dust, which is expelled into the coma upon approach near the Sun, is an important point of study as remnants of the earlier Solar System.

Earlier remote studies have determined that cometary dust is likely to have a physical composition of porous aggregates of sub-micron grains [1]. Further remote studies for the comet 67P have since been supported by the *in-situ* results of the Rosetta mission [2]. Finally, applying material composition of dust as measured from 67P, it was shown that randomly oriented large irregular particles can explain both the coma phase function observations and as densely packed surface, the nucleus phase function [3].

In the light of these observational and modeled results, the understanding of the dynamics of single dust particles is essential in determining the evolution of the size distribution of the dust and the dust behavior inside the coma, to further constrain possible models, especially those explaining coma polarimetry.

2. Dust model

In this work, we consider particles with silicate-like material composition with a complex refractive index $m = 1.686 + \mathrm{i}0.0312$ and density $\rho = 3$ g/cm^3. The shapes of the grains, or the simplest possible single samples in this work, are defined as Gaussian random ellipsoids (GRE) [4] with the standard deviation of the mean radius, $\sigma = 0.125$, and the Gaussian correlation length, $l = 0.3$, based on a smooth ellipsoid with an axis ratio $1 : 0.8 : 0.5$.

A dimer composite particle with an equivalent-volume sphere radius $a_{\mathrm{eff}} = 0.2$ μm of two $a_{\mathrm{eff}} = 0.1$ μm GRE grains

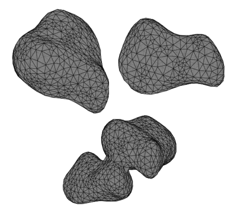

Figure 1: Shape models used in the simple dynamical analysis, with the two monomer grains (numbered 1 and 2 from left to right) separately above, and the composite particle below.

is prepared using the standard routines available in the Python library `PyMesh`. When the GRE grains are discretized as tetrahedra, the composite particle has roughly the number of tetrahedra of the two separate grains combined. The particles are illustrated in 1.

The scattering properties of the particles are completely described by the so-called T-matrix [5], which can be solved for these irregular shapes using a volume integral equation formalism-based solution described in [6] and references therein. The methods above are the basis of a numerical dynamical solver by any kind of electromagnetic scattering interaction [7].

3. Results

The rotational response from scattering of any particle can be summarized using the torque efficiency $\mathbf{Q}_\Gamma$, a dimensionless decomposition of the torque $\mathbf{\Gamma}$, given by

$$\mathbf{\Gamma} = \frac{\bar{u} a_{\mathrm{eff}}^2 \bar{\lambda}}{2} \mathbf{Q}_\Gamma, \tag{1}$$

where $\bar{u}$ is the mean energy density of the incident radiation, and $\bar{\lambda}$ is the mean wavelength. The torque efficiency is naturally dependent on the orientation of the particle with respect to incident radiation. However, for clarity, we consider in the preliminary analysis the situation where the grain is rotated so that its principal axis of major inertia is along the radiation direction. In Figure 2, spline-interpolated torque efficiencies are compared in the range 300–1740 nm, and we see that while the monomer grains have comparable torques subjected to them, the composite particle has clearly differing torques. Due to the larger size of the composite particle, the torque efficiency peaks at a different wavelength, and more importantly the component $Q_{\Gamma,1}$, that is aligned parallel to

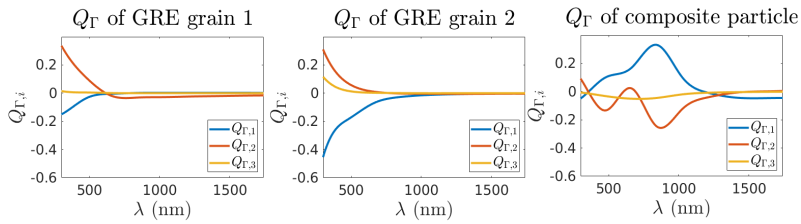

Figure 2: Torque efficiencies of the monomer grains 1 (left), 2 (middle), and the composite particle (right).

the principal axis of minor inertia, has an opposite sign compared to the monomers.

An important quantity of the dynamics of cometary dust is the timescale of angular accelerations. Angular velocity needed to cause disaggregation of dust particles by centrifugal stress σ depends on the tensile strength F_t of the particle. In the context of this work, the upper estimate of the tensile strength of a bulk solid is assumed to be between 0.1–1 GPa [8], and the lower 0.1–1 MPa, a limit which is based on highest values in experimental studies [9] conducted for significantly larger samples. For the centrifugal stress estimates, we use the well-known result for a disk,

$$\sigma = \rho\omega^2 a_{\text{eff}}^2/3. \tag{2}$$

The composite particle neck, that connects the two monomers, is taken to have the cross section of a disk with a radius of 0.1 μm. Using the upper bounds these values, also assuming a distance of 2 au from the Sun, gives an energy density $\bar{u} = 1.70$ nJ/m^3.

We now determine the spin-up time by using the explicit scattering solution as follows. First, we integrate the rotational equations of motion for the composite particle until it reaches a stable rotational state. Second, the average torque over this rotational state is determined, and assuming constant spin-up, the time to reach a certain angular velocity is extrapolated. We find that using these parameters, the minimal angular speed of disaggregation is of the order $\omega \sim 10^7$ rad/s, as indicated by Figure 3. The composite particle reaches this minimum speed in approximately 160 days when starting from rest.

4. Summary and Conclusions

There are two important conclusions that can be drawn from these preliminary results, while noting that observational evidence suggests to model particles beyond the sub-micron scale:

1. Dust particles in the coma are likely to have a highly different stable rotational state after disaggregation, as indicated by the changing torques. This implies that when modeling structural rigidity of different types of aggregates, systematic ensemble differences may arise in a sufficiently large dust population, affecting alignment and thus polarization.

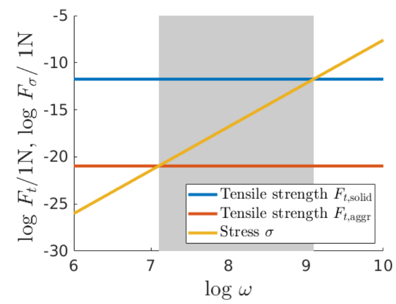

Figure 3: Crossing points for the disaggregating stress and minimal and maximal tensile strengths. Shaded area indicates the area, where some, but not all, of the 0.2 μm particles can be destroyed, given the assumptions made.

2. The studied dust properties and radiation environment that was kept constant were found to result in a situation implying, that disaggregation by radiative effects can be plausible. Further study requires analysis of larger variety of particles and of a gradually changing radiation environment.

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