[PHYSICS IN SPACE]

DUST IN SPACE

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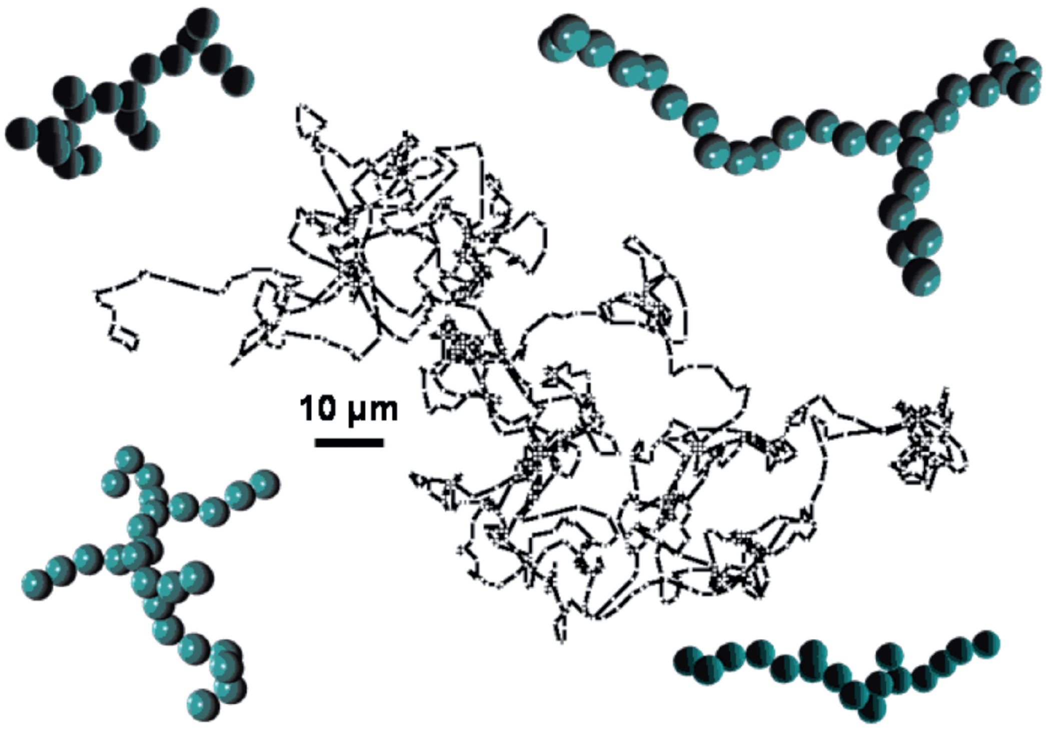
Space is far from being empty. Besides stars and galaxies, microscopic dust particles, often immersed in a gaseous medium, are ubiquitous and play an important role in a variety of cosmic and atmospheric environments. Nanometer- to micrometer-sized particles can be observed in different situations such as:

- stellar outflows, in which freshly-bred material is provided to the chemical reservoir of a galaxy,
- molecular clouds, the cradles of star formation,
- protoplanetary discs, in which planets are born,
- planetary atmospheres and in Earth's atmosphere, where they determine the chemistry and temperature distribution and, thus, climate and weather of the planet, and
- cometary comae and tails, the best source for pristine solar-system material.

In contrast with the much larger dust particles found on the surfaces of solid planetary bodies and in Saturn's rings, small dust grains always experience considerable attractive van-der-Waals or hydrogen-bonding forces whenever they collide with each other. The presence of a gaseous environment generally damps the relative speeds so much that at least some of the inter-particle collisions can result in the sticking of the grains. The dust agglomerates so formed exhibit interesting morphological, mechanical, and optical properties. Systematic investigations of these quantities can help to understand the cosmic material cycle, the formation of the first solid bodies in the solar system, the evolution of planetary atmospheres, and the cometary composition, activity and evolution at successive perihelion passages. In addition, future space missions to the Moon, Mars, or asteroids can benefit from knowledge about the physical interactions of small dust particles. Technical questions of how deep space probes sink in or how well rovers can drive on regolith-covered surfaces can only be answered if the fundamental properties of the small solid particles and their behaviour under different gravity conditions are known. In our own atmosphere, aerosols influence the global energy budget and cause the formation of rain drops, which efficiently cleanse the atmosphere of pollutants, and are thus of important environmental interest. More investigations are also required to better understand the role of aerosols in global climate change.

Why long-duration microgravity conditions?

Laboratory and theoretical studies have shown that collision velocities required for the formation of cosmic dust agglomerates are typically well below 1 ms^{-1}. Most of the above-mentioned astrophysical and planetary environments exhibit rather low gas densities and gravitational accelerations. Ground-based laboratory experiments involving ensembles of dust particles with dif-



◄ **FIG. 1:** Four examples of dust aggregates grown by Brownian-motion-induced collisions [2]. The displayed dust aggregates were reconstructed from three-dimensional microscopic images in a space-shuttle experiment and consist of SiO_2 spheres with 1.9 µm diameter. The centre of the image shows a trajectory of a single SiO_2 sphere with 1.5 µm diameter, recorded in a drop-tower experiment [4]. The trajectory consists of 1024 position measurements and has a total duration of 2.2 seconds. The gas pressure in the experiment was 100 Pa.

ferent sizes or compositions suffer from fast particle losses and systematic segregation or de-mixing due to gravity. Moreover, large dust aggregates are extremely fragile so that they are compressed under their own weight.

Low-gravity experiments can offer the solution. The collision behaviour of *individual* dust aggregates can be studied even in short-duration experiments, *e.g.*, in drop towers or parabolic flights. However, the study of the self-consistent evolution of an *ensemble* of dust agglomerates or aerosol particles requires investigations under long-duration reduced gravity conditions.

To address the issues, astrophysicists, planetary and atmospheric scientists from all over the world joined forces and expertise in an ESA-supported 'Topical Team'. The team defined a long-term research programme along with an experimental facility for the International Space Station (ISS). The following issues are addressed:

- The *dust-dust interactions* control the formation of dust aggregates. These aggregates are characterised by a growth rate, a fractal structure and the distribution of their mass in a particle ensemble. All depend on the relative-velocity fields determined by the physical environment.
- Changing the gas density and the effect of Brownian motion, *i.e.* the *dust-gas interactions*, will also affect the dynamics of the aggregates and eventually their growth and morphology.
- Most of the astrophysical clouds are only observed from the light they scatter. Understanding dust-light interactions thus becomes a necessity to interpret observations. By analysing the light scattered by dust clouds whose composition, optical indices and evolving morphology are known as aggregation proceeds, one can establish a reference database. This requires measuring the angular distribution of the scattered light at different wavelengths, and of its polarised components.
- The case of aerosols in Earth's atmosphere is even more complex because of the combination of *dust-light-gas interactions*. On top of the momentum transfer between the dust agglomerates and the ambient gas, light absorption and differential particle heating also influence the dynamics of the particles in the cloud (photophoresis and thermophoresis).

Learning from space experiments

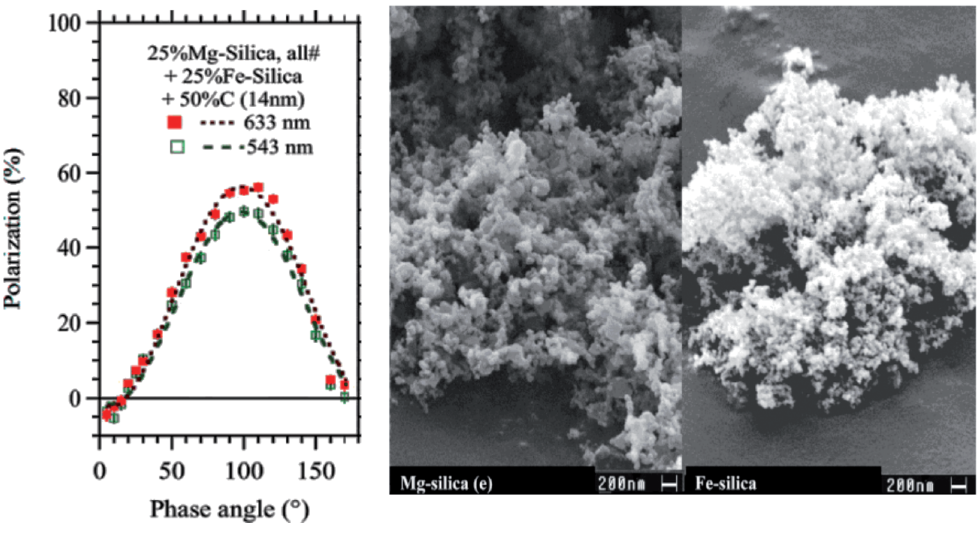
Extensive studies have been carried out in short-term low-gravity environments on the production of monomers and aggregates [1] that are important precursors of cosmic dust particles. Experiments in the drop-tower in Bremen, on a sounding rocket and on the space shuttle showed that large fractal dust agglomerates can be grown in a rarefied-gas environment using the extremely slow Brownian motion of the dust particles [2, 3].

To characterise the individual mass of agglomerates, their structure as well as the random motion of the particles as featured in Figure 1, long-distance microscopy with micrometer resolution and large depth of fields is employed in combination with stroboscopic illumination. High-speed digital cameras are then a must.

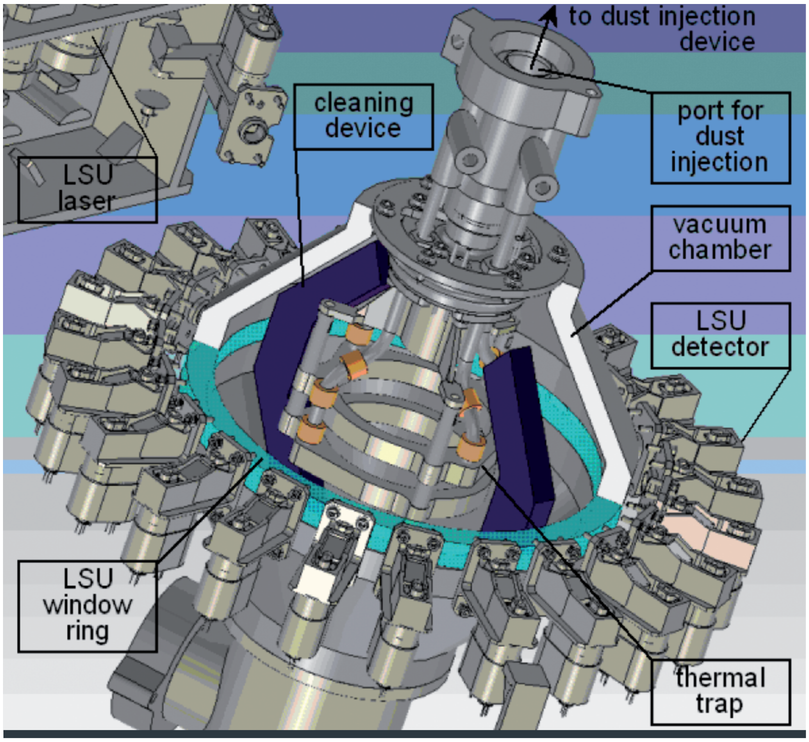
Along with the experimental programme, models were developed on the basis of rate equations and molecular-dynamics-inspired simulations. Matching the model predictions with the agglomerate morphologies and growth rates measured in these two space missions successfully yielded the collision cross sections of fractal dust agglomerates [5,6]. Moreover, the angular scattering and polarisation pattern of the fractal dust agglomerates was measured by a light-scattering instrument.

Further light-scattering experiments on aircraft flying parabolic trajectories and in the laboratory yielded multi-wavelength brightness and polarisation data for dust clouds of various compositions, sizes and morphologies [7]. When compared with remote and in-situ observations of comets, these data, as well as numerical light-scattering simulations on dust grains and fractal aggregates [8], suggest that compact grains and fluffy dust aggregates are present in cometary comae. And both are made up of rather transparent silicates and absorbing organic material as illustrated in Figure 2. The validity of these results was demonstrated - at least for comet Wild 2 - by analyses of the cometary dust samples collected by the Stardust mission [9].

The first long-duration dust agglomeration experiments provided a demonstration of how to operate in a low-gravity environment. Agglomerate sizes of a few tens of microns were observed. These results opened up the perspective of thoroughly studying dust aggregation processes in space.



◄ **FIG. 2: Left panel: percentage of linear polarisation of light scattered in two wavelengths, as measured for levitated dust particles on parabolic flying aircraft. Mixtures of porous grey aggregates of Mg-silica, Fe-silica (featured in the SEM images on the right panel) and sub-μm-sized carbon-bearing materials match the observed scattering properties of cometary dust (see text).**



◀ **FIG. 3:** Sketch of the design of the new instrument for Columbus with its crown of detectors of the Light Scattering Unit (LSU). The inner diameter of the chamber (light blue ring) is about 10 cm (courtesy of Verhaert Space).

A new instrument on Columbus

The instrument under development encompasses an accurately thermally-controlled experiment chamber in conjunction with a thermal particle trap. The trap enables one to confine particle ensembles within the volume of observation. Much larger dust agglomerates can thus form within the duration of the planned experiments of 30 minutes. Besides Brownian motion, whose influence on the agglomeration will be studied in a wide gas-pressure range of 10-1000 Pa, other velocity fields among the dust aggregates can be generated with a particle manipulation system so that also runaway growth of single dust agglomerates can be observed. Being a long-term initiative, the instrument will enable one to study the agglomeration behaviour of dozens of different dust samples. A sketch of the current instrument design is featured in Figure 3; it incorporates solutions to many technical challenges that were jointly tackled by scientists and engineers.

Controlling dust with heat and light

Among these challenges, a *dust-storage device* was developed to store a large number of different dust samples under vacuum conditions and along with it, a *dust-injection device* enables one to choose an individual sample at any given time [10]. A *thermal trap* (similar to a Paul trap for charged particles) has been designed that allows the "holding" of a cloud of dust amidst the intrinsic disturbances of the ISS and thereby the study of highly mass-loaded dust-gas mixtures. The *particle manipulation device* is based on the photophoretic effect by which a dust particle or agglomerate travels (mostly) away from a light source. As the photophoretic velocity increases with increasing dust-aggregate size, large agglomerates can incorporate the small particles in their paths, thus mimicking run-away growth. Moreover, a specific dust agglomerate can be selected and positioned in the observational volume of the diagnostic system for detailed inspection. Measurements in the cloud are made by means of an *overview observation system* including a *particle-tracking* capability, a *digital holography microscopy*, a *long-distance microscope* and a *light-scattering unit*. The instrument developers are looking for an effective window cleaner; unfortunately, no astronaut is allowed to volunteer!

The measurements to be performed in this instrument are crucial for the understanding of the evolution in very dense dusty systems such as the mid-plane of protoplanetary discs in which the essential stages of early planet formation take place. It will be the stepping stone for further investigations on dust-particle research onboard the ISS for cosmic and atmospheric sciences. ■

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