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ORIGO - an ESA M-class mission proposal to understand planetesimal formation and evolution.

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The ORIGO mission was submitted in response to the 2025 call for a Medium-size mission opportunity in ESA's Science Programme. The goal of ORIGO is to inform and challenge planetesimal formation theories. Understanding how planetesimals form in protoplanetary disks is arguably one of the biggest open questions in planetary science. To this end, it is indispensable to collect ground truths about the physico-chemical structure of the most pristine and undisturbed material available in our Solar System. ORIGO seeks to resolve the question of whether this icy material can still be found and thoroughly analysed in the sub-surface of comets. Furthermore, ORIGO will quantify the degree of processing that occurs for planetesimals that formed in the outermost part of the protoplanetary disk.

Specifically, ORIGO aims to address the following immediate scientific questions:

- Were cometesimals formed by distinct building blocks such as e.g. "pebbles", hierarchical sub-units, or fractal distributions?
- How did refractory and volatile materials come together during planetesimal growth e.g. did icy and refractory grains grow separately and come together later, or did refractory grains serve as condensation nuclei for volatiles?
- Did the building blocks of planetesimals all form in the vicinity of each other, or was there significant mixing of material within the protoplanetary disk?
- To what degree have comets been modified through evolutionary processes?

To answer these questions, ORIGO will deliver a lander to a comet where we will characterise the first five meters of the subsurface with a combination of remote-sensing and payloads lowered into a borehole. Our instruments will examine the small-scale physico-chemical structure. This approach will allow us to address the following objectives, each of which informs the respective scientific question:

- Reveal the existence of building blocks of a cometary nucleus from the (sub-)micron to metre scale by exploring unmodified material.
- Determine the physical structure of these building blocks, particularly the size distribution of components and how refractory and volatile constituents are mixed and/or coupled.
- Characterise the composition of the building blocks by identifying and quantifying the major ices and refractory components.
- Quantify the amount of processing of near and deep interior material.

Over the past decade, significant theoretical advances have been achieved in working out possible planetesimal formation scenarios.

The two leading hypotheses for how planetesimals formed from sub-micron dust and ice particles in the proto-planetary nebula can be classified into two groups:

- the hierarchical accretion of dust and ice grains to form planetesimals; and
- the growth of so-called pebbles, which are then brought to gentle gravitational collapse to form larger bodies by e.g. the streaming instability.

These competing theories only have indirect proof from observations. Direct evidence, i.e. ground truths, about the building blocks of planetesimals remains hidden. ORIGO will challenge these theories by examining the physico-chemical structure of the most pristine material available in our Solar System.