Tiny dust particles in space are the seeds of life

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Emily Warrender

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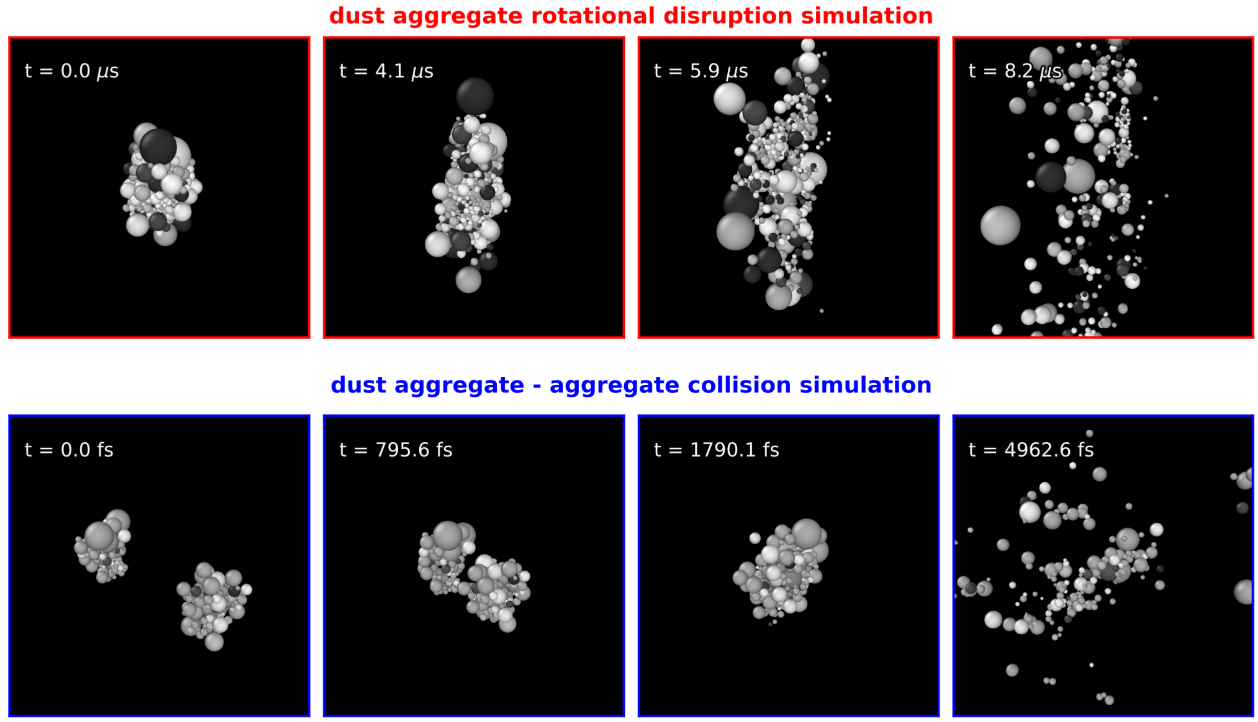

Figure 1. This figure shows two N-body simulation pathways of dust aggregate evolution. The red panels illustrate how rapid rotation can tear apart an aggregate through centrifugal disruption (Reissl+ 2024 A&A, Volume 692, A60, 17 pp.), while the blue panels show how collisions between rotating aggregates may lead to fragmentation (Reissl, Zürn & Klessen 2026 in prep).

Dr Stefan Reissl and Prof Dr Ralf S. Klessen introduce tiny dust particles in space, the seeds of life, in this intriguing field of astronomy research

Life on Earth owes its existence to the presence of tiny dust particles in space. These particles are born in the atmospheres of giant, ageing stars and carried into space by the stellar winds of their hosts. Through countless collisions and sticking processes, the small grains grow into larger and more complex aggregates, which may eventually become pebbles, rocks, and finally planets.

Long before this planetary stage, however, dust already plays a crucial role: it provides surfaces where chemical reactions can create complex organic molecules, the very building blocks of life as we know it. Understanding the life cycle of cosmic dust is, therefore, also part of understanding the story of life on Earth.

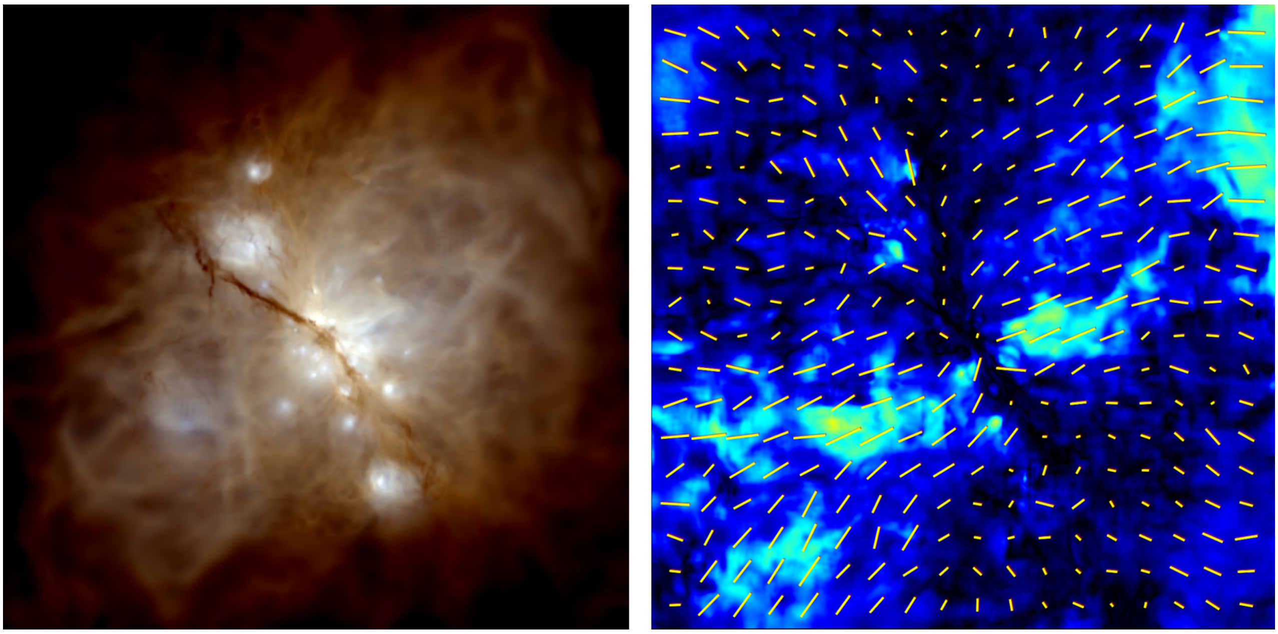

Figure 2. The left panel shows a synthetic image of light coming from stars and interstellar dust in multiple wavelengths, while the right panel displays the corresponding polarization pattern caused by rotating grains. Such synthetic observations help connect microphysical dust models with telescope data, providing crucial tests of how grain growth and rotation influence cosmic dust evolution. (magnetohydrodynamic simulation by Seifried+ 2013, MNRAS, 432, 3320 and images are synthesised with the code POLARIS: https://www.ita.uni-heidelberg.de/~reisslst/)

Discovery of spinning interstellar dust

The presence of flattened interstellar dust particles was first identified in the 1930s and 1940s through observations of starlight reddening and polarization caused by extinction. Since then, modeling the life cycle of dust particles has become an essential part of astrophysics.

Despite significant progress, key questions remain unresolved, for example, the microphysical details of how tiny dust can eventually grow into planetary bodies are still debated.

Observations also show that dust aggregates can spin at extraordinary speeds, reaching up to millions of revolutions per second, most likely driven by starlight and gaseous flows. Yet how this rapid rotation fits into the broader picture of dust evolution and surface chemistry remains a largely unexplored question.

Unravelling dust rotation with supercomputers

Our research team aims to gain a deeper understanding of the impact of dust rotation by using complex multi-physics N-body computer simulations. To do this, we mimic the early stages of the dust life cycle. Similar to the environments of old stars, we allow small primary particles of different sizes and materials to grow through simple collisions and migration processes. This growth produces larger aggregates with intricate internal structures somewhat like snowflakes, though less symmetric. Because of their asymmetry, the aggregates behave like tiny propellers when exposed to starlight, and they begin to rotate once they reach a certain size.

The challenge lies in the enormous range of timescales involved. While the growth of aggregates can take thousands of years, the microphysics of dust, such as the disruption of rotating aggregates, unfolds within fractions of a second. This requires the development of new algorithms and numerical methods. Thanks to modern graphics cards, these methods can now most efficiently be parallelised, allowing us to study a vast variety of dust aggregates with different shapes, sizes, and compositions.

Rotation: A limiting factor in dust growth

The evaluation of our N-body simulation data shows that dust grains are nearly spherical in their earliest stage. However, spherical grains cannot explain the polarization of starlight and are therefore inconsistent with astronomical observations. Our simulations reveal that rapidly rotating grains undergo a deformation phase in which centrifugal forces push the primary particles outward, flattening the aggregates. Left in isolation, such an aggregate would eventually reach a stage where its primary particles gradually disconnect from the main body until the entire structure decomposes back into its initial constituents.

Alternatively, a rotating dust aggregate may collide with another aggregate in space and form a larger structure. However, we find that rotating aggregates are far more fragile than previously thought. Consequently, rapid rotation seems to significantly limit dust growth. Since dust rotation is primarily driven by radiation, our results suggest that the formation of larger pebbles and even planets is heavily suppressed in the vicinity of luminous stars.

Observational implications

To test the plausibility of our simulated dust aggregates, we calculate synthetic polarization images using the Monte Carlo method. In this approach, starlight is traced along probabilistic pathways, during which it becomes polarized and reddened by interaction with our simulated flattened dust aggregates. The predicted polarization patterns depend uniquely on the size distribution and material composition of the dust ensemble under consideration. Such polarization signatures provide crucial constraints for upcoming astronomical observations, offering vital feedback
to further refine and improve our dust models.

Outlook: From dust dynamics to chemistry

Our work provides a reliable microphysical framework for dust growth and fragmentation, including rotation, capturing both the formation of aggregates and the limits imposed by rapid spinning. The next step is to explore how dust rotation affects the surface chemistry of complex molecules on grain surfaces. By linking the physical evolution of dust with its chemical activity, we aim to better understand how the earliest building blocks of life may emerge in space.

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Primary Contributor

Stefan Reissl
Heidelberg University

Additional Contributor(s)

Ralf S. Klessen
Heidelberg University