



PHYSICAL SCIENCE



Solid Fuel Ignition and Extinction (SoFIE) insert supports the Growth and Extinction Limit (GEL) investigation test image taken in the Combustion Integrated Rack (CIR). This image was taken just prior to flame extinction while the green LED was flashing on. The LED allows the fuel surface to be seen during the burn, so that several important parameters can be evaluated, such as how far the flame is from the fuel and how much the fuel is heating up. NASA ID: jsc2024e021222.



HIGHLIGHTS IN PHYSICAL SCIENCE

The presence of gravity greatly influences our understanding of physics and the development of fundamental mathematical models that reflect how matter behaves. The space station is the only laboratory where scientists can study long-term physical effects without the complications of gravity-related processes such as convection and sedimentation. This unique environment allows different physical properties to dominate systems, and scientists are harnessing these properties for a wide variety of investigations in the physical sciences.



The NASA-sponsored **Cold Atom Laboratory (CAL)**, a facility on board the space station, makes use of the space station's microgravity environment to study quantum phenomena in ways that aren't possible on Earth. CAL was launched to the station in March 2018, installed a few months later, and subsequently was used to produce the first Bose-Einstein Condensates (BECs) in Earth orbit.

DISCOVERY

In a recent study published in *Nature*, upgrades to the CAL science module allowed scientists to produce dual-species BECs using ^{87}Rb (Rubidium) and ^{41}K (Potassium) (Figure 22).

A BEC is a state of matter in which clouds of gas are so cold (40 to 70 billionths of a degree above absolute zero), scientists can study properties of matter not otherwise observable.

Dual-species BECs enable the study of the interaction with gravity of two quantum test masses,²¹ a key capability needed to test the universality of free fall (UFF) and Einstein's theory of general relativity. CAL produces the ultra-cold gasses using an atom-chip trap with strong confinement capabilities, laser facilities to form magneto-optical traps, and microwave evaporative cooling techniques in microgravity.

Current experiment runs contain thousands (10^3) of atoms per species, but the CAL team acknowledges greater than 10^6 atoms per species will be needed to take full advantage of microgravity and set new records for sensitivity. Future work for the five CAL science teams includes increasing the number of trapped atoms per experiment run, studies of quantum chemistry and fundamental physics, and the nature of dark energy and dark matter.

CAL experiment hardware with enhanced and new capabilities is already in development on the ground. Results from CAL help us to better understand the physical world and find answers to questions that cannot otherwise be answered.

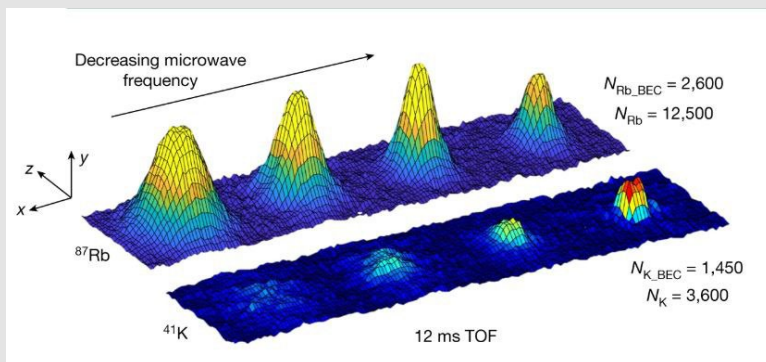


Figure 22. Simultaneous production of potassium and rubidium BECs in critically low temperatures. *Image adopted from Elliott, Nature.*



BENEFITS FOR HUMANITY

The NASA investigation [Optical Imaging of Bubble Dynamics on Nanostructured Surfaces](#) uses an optical imaging system to observe how different types of nanostructured surfaces affect bubbles generated by boiling. The interplay and competition between surface tension, buoyancy, and capillarity (a force that moves liquid independent of gravity, such as a paper towel absorbing water) affect bubble generation, growth, and detachment. In microgravity, researchers can eliminate buoyancy and focus on the roles of surface tension and capillarity.

The manipulation of bubble dynamics via nanostructured surfaces could improve thermal management and enable the development of bio-sensing technologies by using the physical properties of bubbles to detect particles in biological tissue.

In a new study published in *npj Microgravity*, researchers designed a quartz cuvette that contained deionized water and a microstructured copper surface attached to the top inner wall of the cuvette.²² Via electrochemical reactions, porosity of the surface was manipulated by adjusting the molarity of the copper sulfate in which the surface was created (i.e., larger pores were obtained for surfaces with increased molar concentrations). Four different types of surfaces ranging in pore size were fabricated. A heater was attached to the exterior wall of the cuvette.

Results showed that vapor bubble production is up to 30 times faster in microgravity than on Earth (Figure 23). Bubbles in space are also larger and collapsed after about three minutes. However, surfaces with finer microstructures resulted in slower and longer nucleation time because of enhanced heat transfer. These outcomes suggest that the conditions of reduced convection flow, fast temperature rise, and surface type in microgravity influence bubble production and growth. Consistent differences between microgravity and ground experiments demonstrate that surface bubble dynamics are primarily driven by changes in gravity and temperature, not by surface porosity size.

These results could improve thermal systems such as the cooling of electronics, refrigeration, nuclear reactors, and heat transfer in the metal or oil industries. Additionally, fundamental insights into bubble dynamics could improve sensors that use bubble formation, including those that test biomarkers for cancers, contributing to better medical diagnoses in space and on Earth.

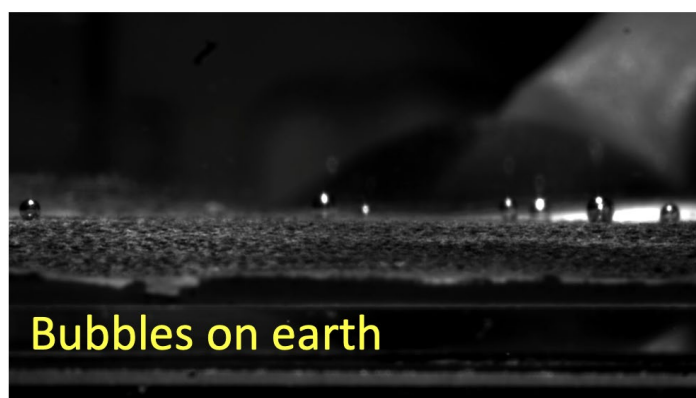
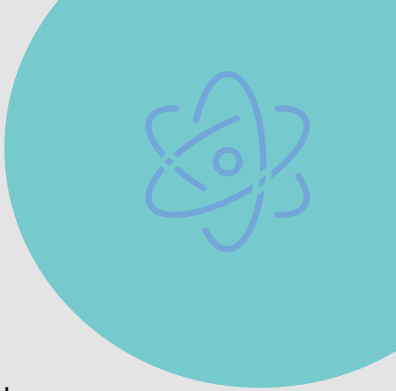


Figure 23. Comparison of bubbles generated in space versus Earth. Image provided by the *Optical Imaging of Bubble Dynamics on Nanostructured Surfaces* research team.



BENEFITS FOR HUMANITY

JAXA's **Electrostatic Levitation Furnace (ELF)** is designed to melt and solidify materials by applying a method that does not require the use of containers and can be achieved by suspending samples in mid-air. Researchers can levitate and position materials as needed using the force of attraction or repulsion between charged samples and electrodes, as well as feedback from a high-speed camera. This unique facility enables the examination of thermophysical properties (density, surface tension, and viscosity) that are difficult to measure on Earth. Such studies are supporting the development of manufacturing processes using local resources from space, which are critical to the advancement of the low Earth orbit economy and creation of lunar habitats.

In a single-case study recently published in *npj Microgravity*, researchers compared the properties of an inorganic compound (a titanate) and its derivative products (glass and crystal).²³ Identical pellet-like samples were prepared for space and ground experiments (Figure 24). The samples in microgravity were heated using four semiconductor lasers for several minutes and then cooled freely.

Researchers found that glass products processed on Earth and in microgravity exhibit nearly identical atomic structures, but the cooling rate is slower in microgravity. Differences in cooling rate between Earth and microgravity are attributable to the absence of forced convection in electrostatic levitation. This result demonstrates that the same titanate-derived glass can be manufactured in space and on Earth.

Additional analyses showed significant differences between the microstructures of the crystalline samples. Some microgravity samples were highly unusual and exhibited streaks of crystal grains that spanned across the entire sample, suggesting differences in the crystal nucleation and growth, likely due to unstable levitation (Figure 25).

Previous research on melt processing in microgravity has focused on metallic materials, and this study contributes to a new understanding of processing oxide glass materials with applications in optical devices and advanced display screens.

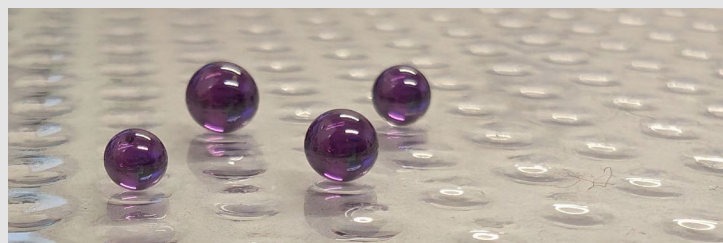


Figure 24. Neodymium titanate glass (approximately 2 mm in diameter) used for experimental and control conditions.



Figure 25. Microgravity samples show fractured structures upon crystallization. *Images provided by the ELF research team.*



BENEFITS FOR HUMANITY

The **JAXA Colloidal Clusters** investigation explores the formation of clusters made up of negatively and positively charged particles suspended in liquid in microgravity. Researchers use the electrostatic attraction between these oppositely charged particles (polystyrene and titania) to form clusters. The microgravity conditions on the space station also help to eliminate the effects of gravity on the materials and minimize the impact of sedimentation. This study specifically aims to identify tetrahedral clusters – structures composed of four triangular faces – to enhance fundamental understanding of how these clusters form in space.

In a recent study published in the *International Journal of Microgravity Science and Application*, researchers successfully immobilized these clusters on the space station using a gel more resistant to aging.²⁴ Previously, the JAXA Colloidal Clusters experiment fixed colloidal particles in liquid solutions, but this new method developed a gelation method that can be used over extended periods. This advancement addresses the challenges of long waiting times and storage needs in space experiments. While gel immobilization is a common practice on Earth, space experiments often require a longer interval between the preparation of solutions and the actual experiments. Preparing this new gelation technique is expected to be valuable for future space experiments involving various soft matter systems.

These gels were specifically created to ensure low background interference in all the analytical techniques used to analyze the samples, including neutron scattering experiments at Australia's Nuclear Science and Technology Organisation (ANSTO).

The structures within tetrahedral clusters can be studied as models for understanding particle aggregation behavior in nature.

By characterizing these clusters, scientists can gain insights into the building blocks of future photonic materials—materials that manipulate light. The tetrahedral clusters returned to Earth are of particular interest because their size allows them to scatter light in the visible to near-infrared range, making them useful for optical or laser communications (Figure 26).

These clusters hold potential for the development of novel optical materials, and even for possible cloaking devices. Each new advancement in optical communications can contribute to improved data transmission rates between Earth and deep space exploration missions such as missions to the Moon or Mars.

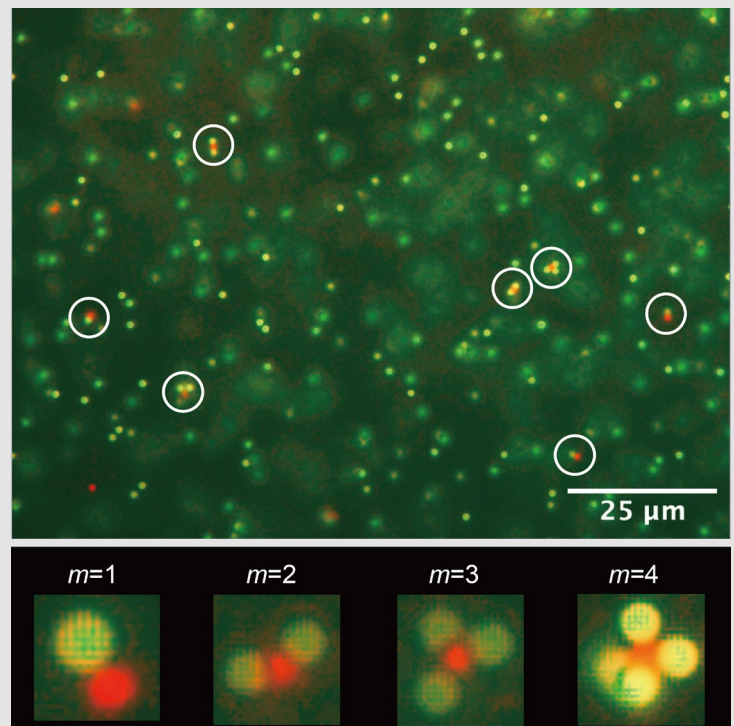
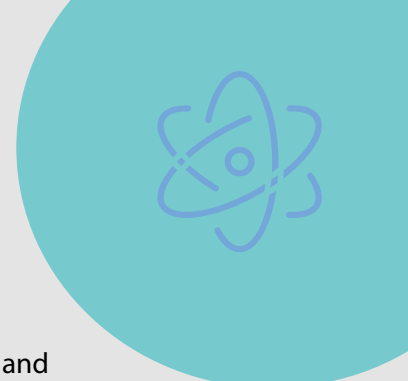


Figure 26. Fluorescence micrograph of colloidal clusters obtained in a space experiment. The sample was immobilized in a polymer gel. Magnified images of clusters with association numbers $m = 1-4$ are also shown. Negatively charged (green fluorescence) and positively charged (red fluorescence) polystyrene particles were used. Image provided by the JAXA Colloidal Clusters research team.



BENEFITS FOR HUMANITY

The ESA investigation [Multiscale Boiling](#) examines the process of heat transfer from a surface to a liquid, causing the liquid to boil and then change into a vapor. Researchers use a multiscale modeling approach (i.e., observations across multiple levels of time and space) to learn about this phase-change in a pool boiling configuration. Although boiling is commonly seen in everyday life, it is a complex process with applications in chemical processing, electricity production, and thermal management. Studying the dynamics of boiling heat transfer in microgravity allows researchers to observe changes that are too small or too fast on Earth due to convection and buoyancy.

New research published in the *Journal of International Communications in Heat and Mass Transfer* demonstrated bubble growth using a coolant (N-perfluorohexane) in a boiling cell on station. The set-up included a focused laser that heated a foil surface for a few milliseconds without shear flow or electric field.

The initial temperature state of the fluid, known as subcooling, varied from 1°C to 5°C. Results showed that bubbles formed faster when the initial temperature of the fluid was 1°C than when the fluid temperature began at 3°C or 5°C. Delayed bubble formation occurred when the laser had to transfer more energy to the fluid.²⁵

Moreover, bubbles grew larger when the initial temperature was 1°C and remained attached to the heater longer. Bubble shape changed from being elongated along the horizontal axis or the vertical axis. This back-and-forth reshaping led to bubble detachment (i.e., condensation), with eventual equilibrium of the bubble into a round shape (Figure 27). Once bubbles detached, they shrank at first but then remained unchanged for several seconds. These condensed bubbles then drifted downward and merged with attached bubbles. Researchers noted that smaller bubbles from fluid starting at 5°C appeared to condense faster.

These results indicate that subcooling fluid temperature influences bubble growth and condensation, potentially revealing mathematical laws in microgravity that could be explained in three stages 1) laser-induced growth, 2) round shape stability, and 3) uniform bubble growth. This pioneering investigation informs the design of space applications such as cryogenic fuel storage, propulsion, and cooling systems for electronic equipment.

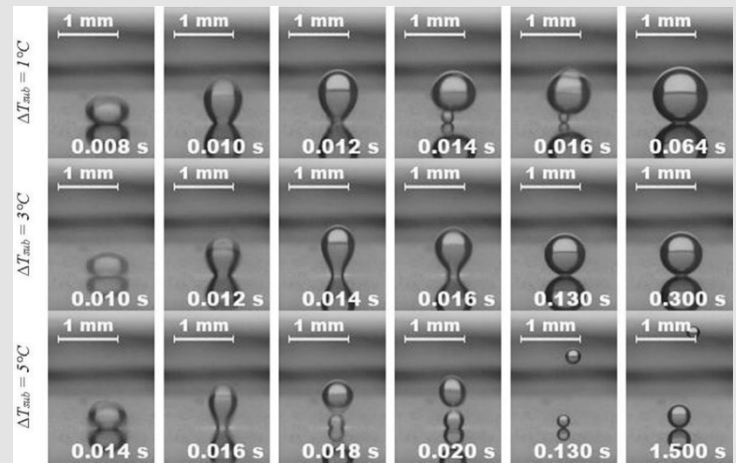


Figure 27. Changes in bubble shape, stabilization, and detachment at different temperatures. *Image adopted from Ronshin, Internal Communications in Heat and Mass Transfer.*

If you are interested in learning about facilities and opportunities for research in fluid physics, as well as funding and launching research to station, read our [Researcher’s Guide to: Fluid Physics](#).



BENEFITS FOR HUMANITY

The Fundamental Research on International Standard of Fire Safety in Space – Base for Safety of Future Manned Missions

(FLARE) investigation sponsored by JAXA, explores the flammability of different materials in microgravity. Prior studies have shown that the level of oxygen required for combustion decreases in microgravity, while low flow speed can increase the combustion requirement and suppress flame spread.

In a new study published in the *Proceedings of the Combustion Institute*, researchers used multiple types of cameras to analyze flame spread inside a pressure and temperature-controlled wind tunnel.²⁶ Results of flammability testing in microgravity were used to verify predictions made in ground-based activities.

Researchers successfully replicated orbital experiments of combustion and flammability in microgravity. Nineteen experiments showed radiation loss and reduced flame spread as the opposed flow of oxygen increased (Figure 28). Results indicated that original calculations from orbital experiments overestimated the flammable region in areas of reduced air flow, after which the researchers modified their model to accurately predict the flammability limit. Researchers also found that flow speed impacts the shape of flames. Results could be used to predict flammability limits of thin, flat objects and improve understanding of flame spread in a lower-gravity environment.

Combustion science improves knowledge to support fire safety during space travel. As humans explore different gravity levels, oxygen concentrations, and pressures, there is a need to predict the flammability of various materials.

The FLARE investigation demonstrates a way to predict flammability in microgravity that could fill knowledge gaps and significantly improve fire safety aboard spacecraft on future exploration missions. New methods for evaluating the flammability of materials in high flow speed conditions also have potential applications for evaluating and reducing fire hazards on Earth.

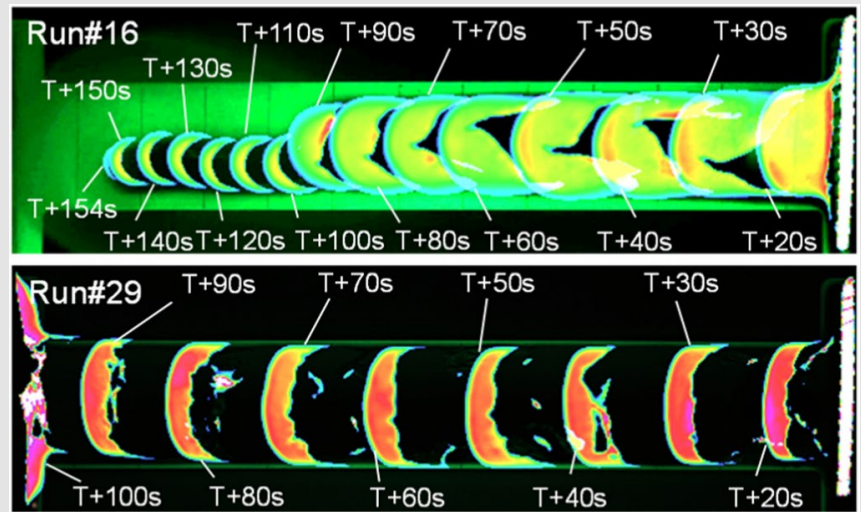


Figure 28. Sequence of infrared images showing fire extinction over time. Opposed flow of oxygen was higher in run #16 than in run #29. Image adopted from Takahashi, *Proceedings of the Combustion Institute*.

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