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Condensed-Matter Physics

Fig.1

The Condensed-Matter Physics program at CNES is based on a Research Group for Fundamental and Applied Sciences in Microgravity (GdR MFA). This GdR brings together French laboratories that use microgravity to support research. It involves about 40 laboratories of the CNRS, the CEA and *Grandes Ecoles* (French top-ranking universities), and around 150 researchers in all domains of matter physics.

At the GdR's annual congress, researchers have the opportunity to present the progress of their work and exchange on the resources and constraints linked to microgravity experiments. Experiments are mainly made in the NOVESPACE ZERO-G aircraft but also in drop towers, in probe-rockets, in the CEA's magnetic compensation chambers and in the International Space Station (ISS) for projects in cooperation with foreign agencies or as part of ESA's ELIPS European Programme[1].

Most GdR scientists are also involved in ESA's Topical Teams which brings together scientists across Europe by research topics. In some cases, these research projects lead to the development of instruments which are operated by ESA in the ISS.

The Condensed-Matter Physics program covers the following domains: combustion (solid or gas), supercritical fluids, fluid physics (flows and boiling), complex fluids (foams, colloids and granular materials), materials science and biophysics.

The CNES program helps laboratories adapt their scientific instruments to the constraints of the means of access to microgravity. It also promotes international meetings and organizes cooperation programs with foreign agencies. Therefore, the scientific expertise of the French laboratories and the possibility to use the ZERO-G aircraft for experiment development are often the subject of agreements with other agencies to implement experiments in sounding rockets or in the ISS for long-duration microgravity experiments.

For these activities, CNES also benefits from CADMOS[2] which prepares and organizes experiment monitoring, both in the ZERO-G aircraft and in the ISS. CADMOS monitors the experiments by ensuring direct communication with the scientists in their laboratory and the scientific instruments on board, which ensures real-time monitor-

Fig.2

ing of the experiments. It is in contact with astronauts via NASA to coordinate the command and data transfer.

The access to microgravity is essential to counter the main effect of gravity which conceals the other forces at stake in physical interactions on the ground. It allows to simplify equations and to validate digital models with very specific environment conditions that let the weakest forces reveal themselves. Although the laws of physics benefit the most from these breakthroughs, every single GdR laboratory is in contact with the industrial sector to file patents and submit innovative applications.

In the past two years, a particular effort has been made to place Condensed-Matter Physics at the service of other scientific fields. The physics of granular material can help obtain a better understanding of how asteroids formed; the study of condensation phenomena can help understand climate variations, capillary wave turbulence can contribute to explain the appearance of rogue waves at the surface of the ocean and biophysics can explain blood flow dysfunctions. Therefore, this interdisciplinarity, spread to other branches of physics and thanks to experiments in microgravity, will reveal more insight into the forces at stake in the phenomena around us and participate in the preparation of space exploration.

(1) *European Programme for LIfe and Physical Sciences.*

(2) *Centre d'Aide au Développement des Activités en Micropesanteur et des Opérations Spatiales.*

Fig. 1: CNES parabolic flight campaign aboard the new Airbus A310 Zero-G in May 2015. *© CNES/Rouquette Sébastien, 2015*

Fig. 2: First parabolic flight campaign aboard the 310 Zero-G in May 2015. *© CNES/DLR/ESA/Novespace/Schneider Sven, 2015*

Fig.1

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Condensed-Matter Physics

Oscillating pattern formation in alloy solidification

During the solidification process, complex patterns are formed at the interface between solid and liquid, playing key roles in understanding physical phenomena. They occur in nonlinear growth rates observed in nature such as combustion, fluid dynamics, geology and biology. During solidification, an oscillating pattern forms in which each cell grows as its neighbors decrease. Gravity hampers these breath-like oscillations in ground experiments, but they have been studied and characterized via interferometry in the International Space Station.

Metal alloy structures are used in many applications including civil engineering and transportation industries. The mechanical properties of the material are strongly affected by its microstructures arising from the solidification process, which is why microstructure formation must be mastered to produce materials with specific properties. Solidification is a model system – generic of nonequilibrium phenomena in physics – for structure formation and pattern organization. During directional solidification, the instability of the solid-liquid interface leads to the formation of dendrites or cells of tens up to hundreds of microns. Three-dimensional pattern formation is hard to study in ground experiments because of the convective mass in the liquid transporting alloy components, thus resulting in inhomogeneous macroscopic concentrations.

The French Space Agency (CNES) and NASA have collaborated on the DECLIC project aboard the ISS. Scientists at the IM2NP (UMR CNRS 7334, Aix Marseille University, France), Northeastern University (Boston, Massachusetts) and Iowa State University (Ames), have carried out a series of solidification experiments in the Directional Solidification Insert (DSI). Thanks to telescience and to the CNES control center (CADMOS, Toulouse) a "real time" monitoring was carried out from a ground-based laboratory, thus optimizing experiments (management of control parameters, cameras, focus, etc.) and improving results. Back on Earth, the space experiments were then conducted again so as to evidence the impact of convection.

The experiment system provided high quality images of the microstructure. Science teams are still poring over this wealth of new data: they will improve our understanding of microstructure formations and provide benchmark data to develop theoretical and digital models for process optimization and for designing tailored materials.
The major results include the observation of a cellular structure with breath-like oscillations, expanding and contracting rhythmically. Oscillating cells are usually noncoherent due to array disorder, with the exception of small areas where the array structure is regular and groups of cells synchronize into coherent oscillations (see the hexagonal array in Fig. 1, where three patterns are oscillating with a 120° phase difference). The cells of the most advanced pattern sometimes inhibit others, but roles are periodically reversed. These findings demonstrate a strong interaction between the array structure and its dynamics. They were published in the Physical Review Letters [1] and received the "American Astronautical Society 2014 Awards for Top Discoveries in Microgravity on International Space Station".

Two other space experiment campaigns on different samples are planned. One will complement data on dendrites, the other on the secondary instabilities of cell arrays.

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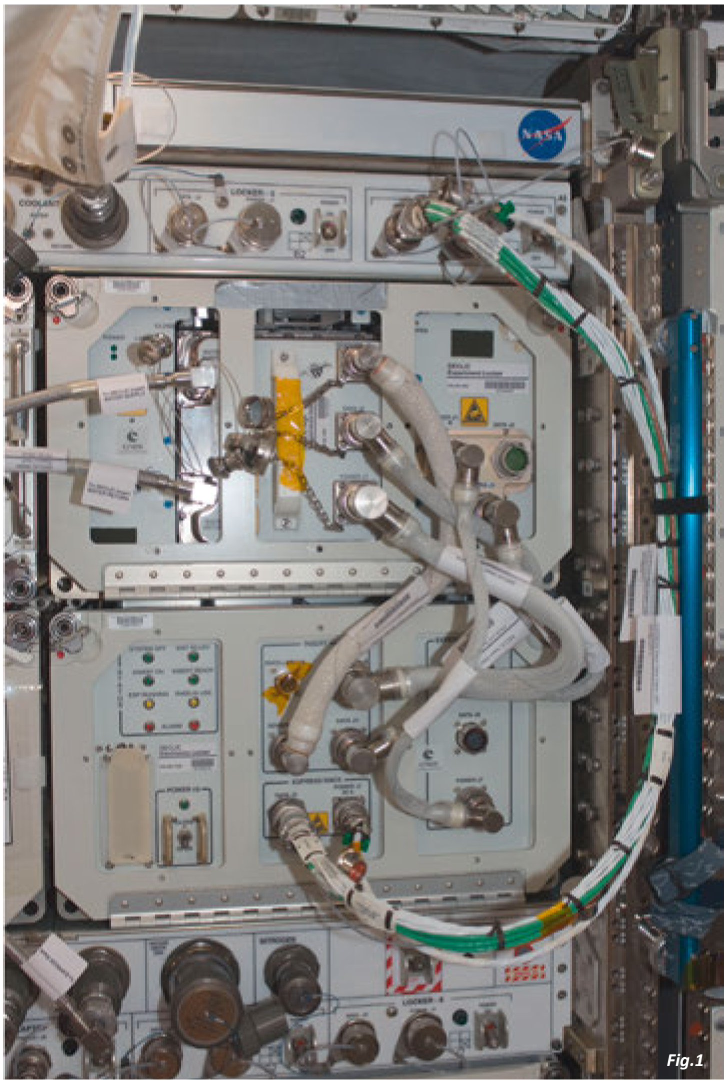

Fig.1

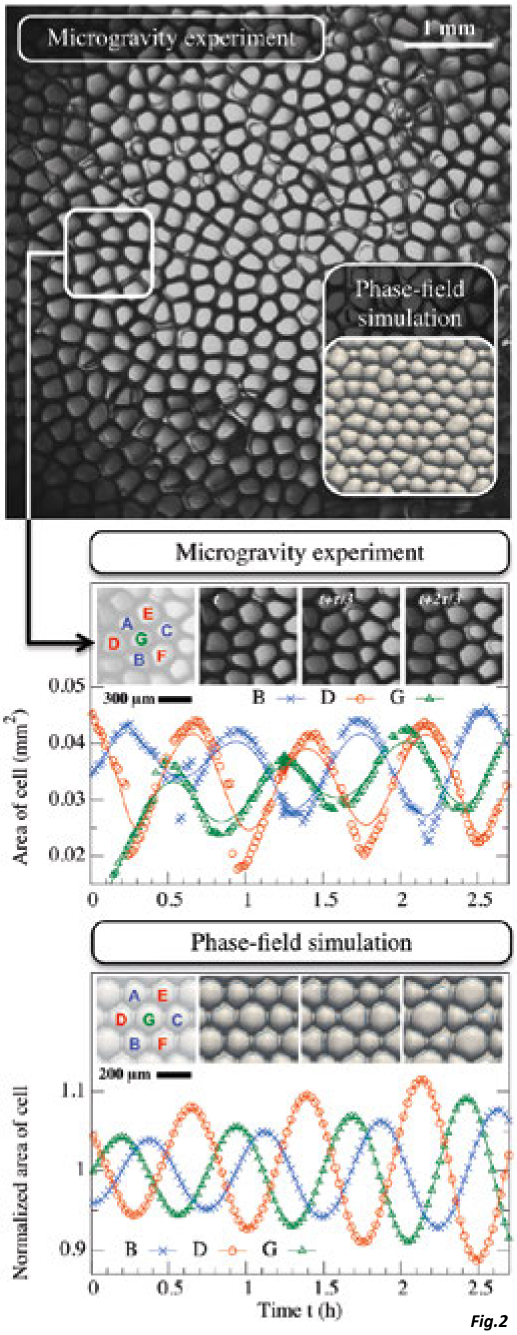

Fig.2

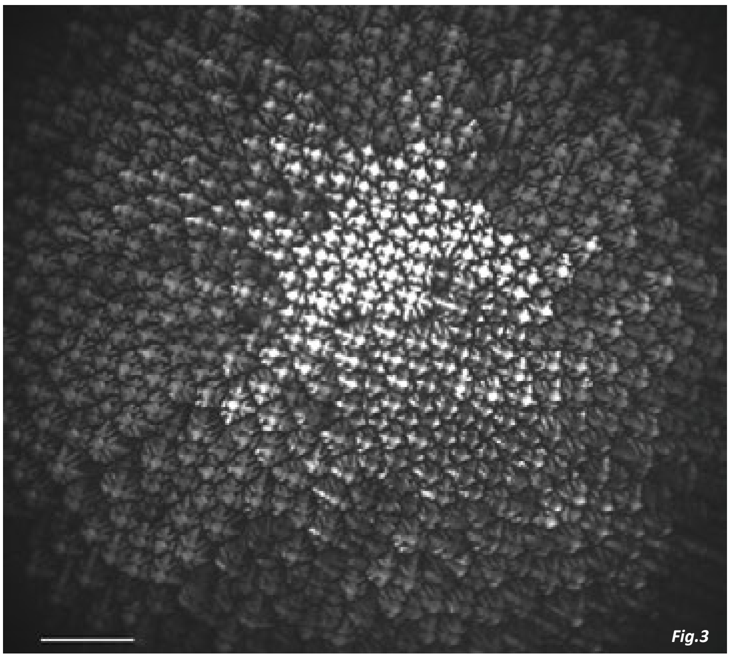

Fig.3

Fig. 1: Declic installed into an Express Rack aboard the ISS. *© NASA*

Fig. 2: Oscillating cellular patterns; the interface between solid and liquid seen from the top (Microgravity experiments in the Declic-DSI. Transparent alloy model of metal alloys.) Oscillations are globally noncoherent, but some oscillating arrays display a regime of phase-coherent oscillations, such as the hexagonal array marked in white. *© N. Bergeon, B. Billia, Aix-Marseille University & CNRS, France, R. Trivedi, Iowa State University, USA.*

Fig. 3: An example of a dendritic pattern; the solid-liquid interface seen from the top (Microgravity experiments in the Declic-DSI. Transparent model alloy of metal alloys.) © Springer Science

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Condensed-Matter Physics

Universal behavior of critical and supercritical fluids


Fig.1

Under ordinary conditions of pressure and temperature, we distinguish the three well-known states of matter, namely gas (air), liquid (water) and solid (glass). A decrease or increase in temperature usually leads to a transition of matter from one state to another. Aside from these standard transformations (boiling, liquefaction, melting, solidification, etc.) where the volumes occupied by matter are extremely different, it is also possible to achieve more subtle situations by compressing a precise amount of material which is heated or cooled at constant volume. When the temperature, pressure and density of a pure substance are close to the critical point, gas and liquid become indistinguishable, and are referred to as a critical or supercritical fluid. The material then adopts nonequilibrium properties and behaviors, governed by the critical universality predicted by methods of renormalization group in field theory.

Thanks to the study of a single pure fluid, one can characterize the thermo-physical properties of all other fluids and validate the theoretical approaches applicable to very different physical systems (fluids, liquid mixtures, solid magnets, etc.). In addition, controlling the singular variations of these properties over several orders of magnitude allows experiments with operating conditions that are similar to those of geophysical and astrophysical flows.

For several years, the ICMCB[1] institute has been studying fluid properties under supercritical conditions. Gravity forces cause density gradient stratification in the cells or make the fluid unstable near its critical point, which is why experiments are conducted in microgravity. To benefit from the best mechanical, thermal and optical environment available today in an onboard facility, these studies are made with sulfur hexafluoride (SF_6), whose characteristic feature is that its gas-liquid transition at critical temperature is close to 45 °C and its critical pressure is moderate (3.7 MPa).

The International Space Station (ISS) is the ideal place to conduct these experiments. In 2000, CNES signed an agreement with NASA to implement a scientific insert

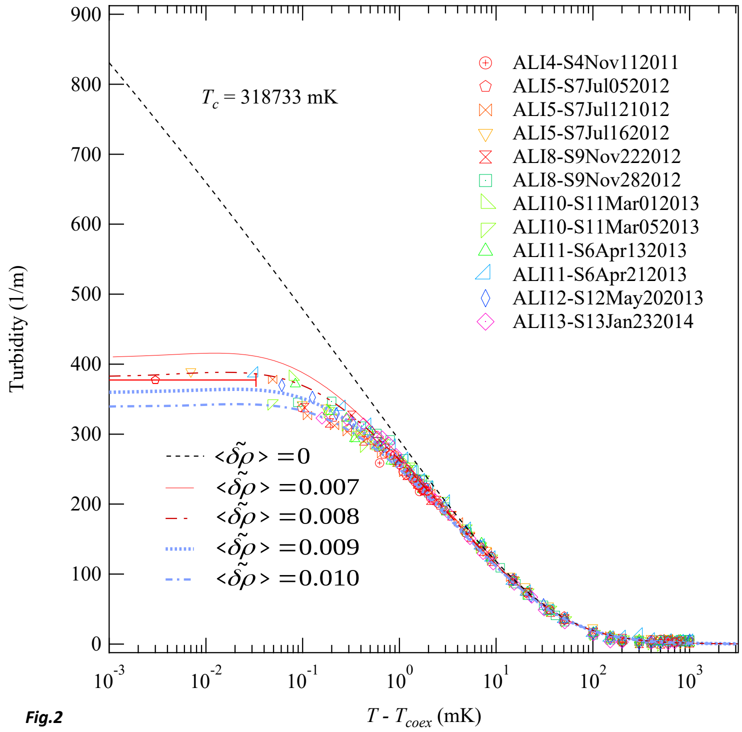

Fig.2

Fig. 1: Backdropped by a blue and white part of Earth, the International Space Station is featured in this image photographed by an STS-130 crew member on space shuttle Endeavour after the station and shuttle began their post-undocking relative separation. *© NASA, 2010*

Fig. 2: Lin-log plot of turbidity τ (m-1) according to temperature difference T - Tcoex (in mK), obtained for the SF_6 fluid. Light transmission measurements from the Ali Declic insert were conducted up to several µK temperature distances. The measurements are compared to the theoretical turbidity of the equation of state model with no adjustable parameter for various density deviations compared to critical density. The black dotted line represents the turbidity calculated for the critical isochoric. *© ICMCB/Yves Garrabos*

dedicated to these "critical fluid" experiments in the DECLIC instrument. It was developed by CNES and has been operating since 2009, alternatively with another scientific insert using water and aqueous mixtures, as part of a close collaboration between the ICMCB and NASA's JPL and Glenn Research Center laboratories.

The results of these studies were the subject of numerous publications as well as a recent synthesis [1]. In June 2015, a short communication in the international journal *Physical Review* used turbidity measurements in SF6 near its critical point to illustrate the expected universal behaviors of a critical fluid [2]. The light scattering caused by critical density fluctuations increases as the critical point is approached, resulting in turbidity increase measured by the attenuation per unit length of light intensity of a laser through the cell. As shown in Fig. 2, turbidity measurements were conducted with accuracy by approaching the phase separation temperature at a few microKelvins. These temperature distances are beyond reach on Earth where the fluid becomes stratified under its own weight, making cell density non-homogeneous. Data analysis has been conducted without adjustable parameter using a universal equation of state model in line with the theoretical predictions of the three-dimensional uniaxial Ising model universality class. We still have to optimize the critical point density approach which will be studied next time the insert is used, with a cell filled to critical density.

Beyond the progress brought by these experiments to non-equilibrium media physics, it is worth pointing out that the universal nature of these studies on model fluid is relevant to many burgeoning application fields where process expertise often implies a better knowledge of physicochemical properties of the industrial fluids involved. There has been, for many years, a strong development of processes where chemical reactions are conducted in a supercritical fluid in order to combine the respective advantages of chemistry in gaseous media and of solution chemistry. The industrial sector already depollutes, desalinates, neutralizes and destroys waste by cold combustion in supercritical fluid medium. These so-called "green processes" must still improve on Earth for the benefit of many. They must also be made operational in microgravity conditions to benefit space exploration.

The future DECLIC-Evolution instrument is currently under study at CNES, in cooperation with American laboratories, for two purposes. The first is to determine the validation parameters required to use theoretical models and numerical simulation methods of supercritical media. The second is to study and characterize matter transfer conditions associated with cold combustion mechanisms in supercritical water. The instrument is expected to be installed in the ISS as of 2021 and will help continue this research in a field where matter properties open an experimental investigation that would accurately validate the theoretical approaches of nonequilibrium statistical physics.

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