Ice in Space

—Ice Crystal Growth Experiments Conducted in ISS-Kibo—

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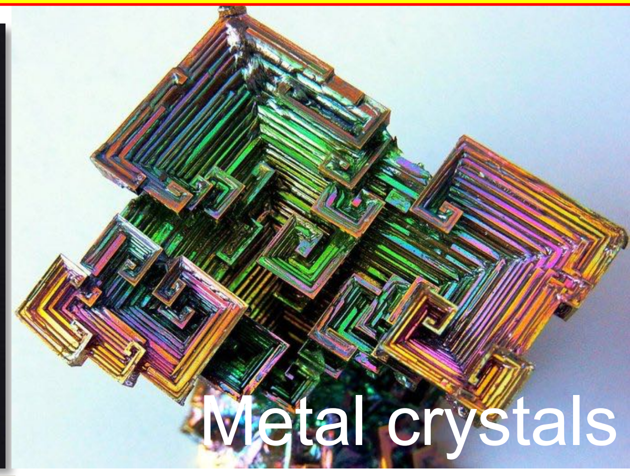
Crystals

Why and how are these beautiful patterns formed in nature?

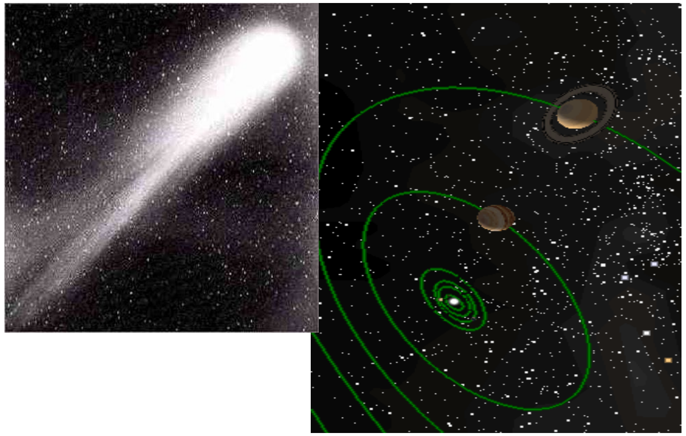


Crystal growth mechanism is a key concept for the material science researches.

Ice crystals

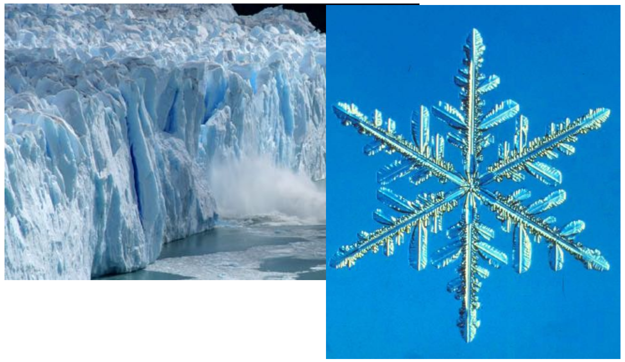
Water: one of the most abundant and ubiquitous materials on earth.
--> Its phase transition governs various important phenomena on earth.

Cosmic evolution/ Planetary Science



Origin of solar system
Molecular evolution
Planetary ice

Meteorology/Environ-mental science/ Glaciology



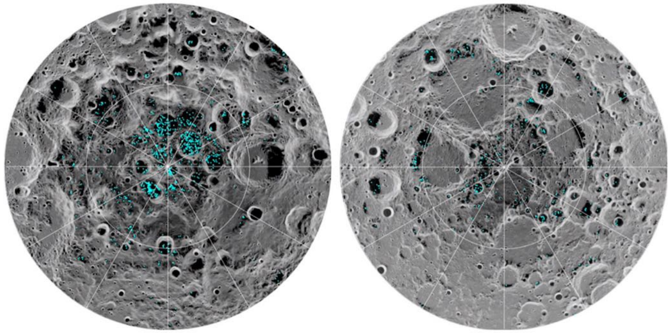
Solid and liquid precipitations
Aerosol
Ice sheet and glacier
Ozone hole etc.

Biology in subzero environment

Biological evolution in ultimate environment
Strategy for freezing inhibition

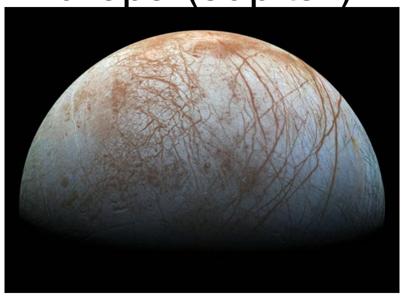
Crystal growth of H_2O controls various natural phenomena occurred in cryosphere !

Ice crystals: most common material in the planetary system

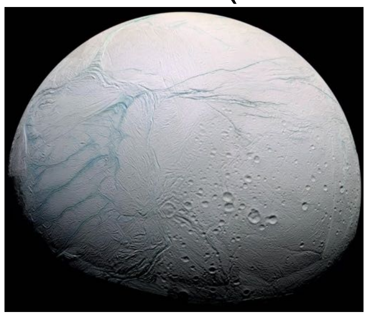


Moon

Europa (Jupitar)



Enceladus (Saturn)



Ice crystals have been found on the Moon, Mars, Europa, Enceladus and so on.

Ice can become the source of water supply for the interplanetary explorations.

Ice strongly relates to the presence of life on the planets.

This is the other importance for the ice crystal growth experiments.

Why do we study the ice crystal growth?

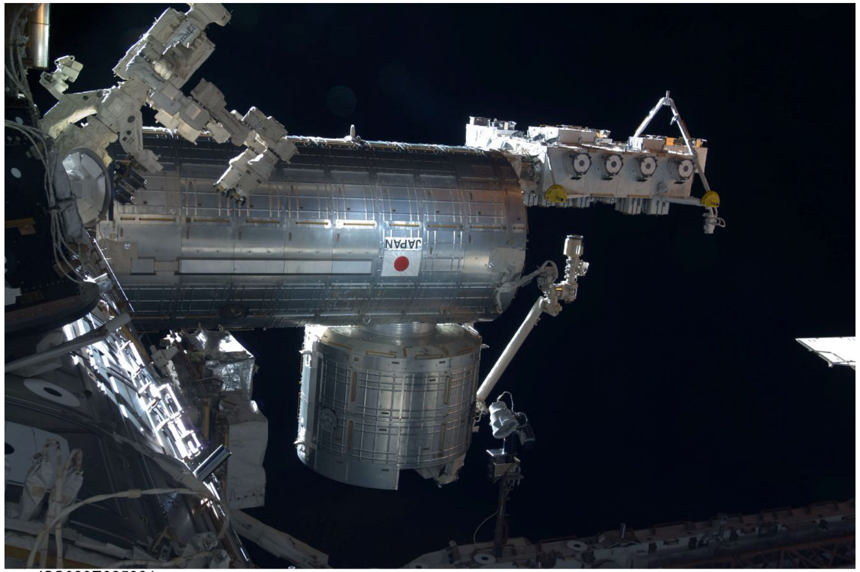
Ice crystal is one of the key materials to study the fundamentals of crystal growth: Nucleation, Pattern formation, Morphological instability, Growth kinetics, Surface melting, **Impurity effect**, etc.

Water (Ice) is the ubiquitous material on the earth as well as in our planetary system. The phase change kinetics among three phases of water is very important to drive various natural phenomena which occur on the earth.

Researches of ice crystal growth are crucial for understanding these fundamental subjects.

Ice crystal growth projects conducted in space

Japan Experiment Module "Kibo" of ISS was used for our space experiments



ISS020E025981

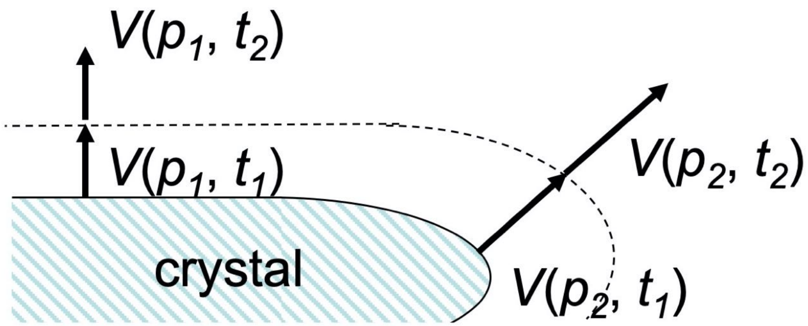
Since the crystal growth is generally the time consuming phenomenon, LONG-TERM microgravity condition achieved only in such the spacecraft as ISS is essential for the crystal growth experiments.

Projects for ice crystal growth in space（Carried out only in Japan)

- Get Away Special (1983, STS-6): Growth of snowflakes (Asahi Shimbun)
- Sounding rocket experiment (1998, TR-1A7):Growth of ice crystal (NASDA)
- Ice Crystal 1(2008-2009, ISS): Pattern formation of ice crystals (JAXA)
- Ice Crystal 2 (2013-2014, ISS):Impurity effect for ice crystal growth (JAXA)

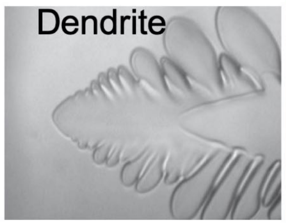
In-situ observation of pattern development and precise measurements of growth rates

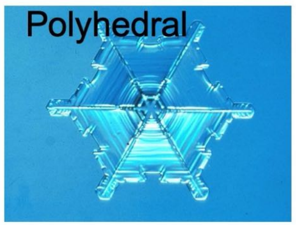
Growth rates are given as functions of the point on a crystal surface (*p*) and the growth time (*t*).



Growth rate $V = f(p, t)$

Morphological instability



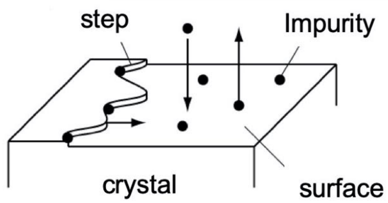


Mullins-Sekerka instability

Berg effect

Ice Crystal 1 project

Impurity effect



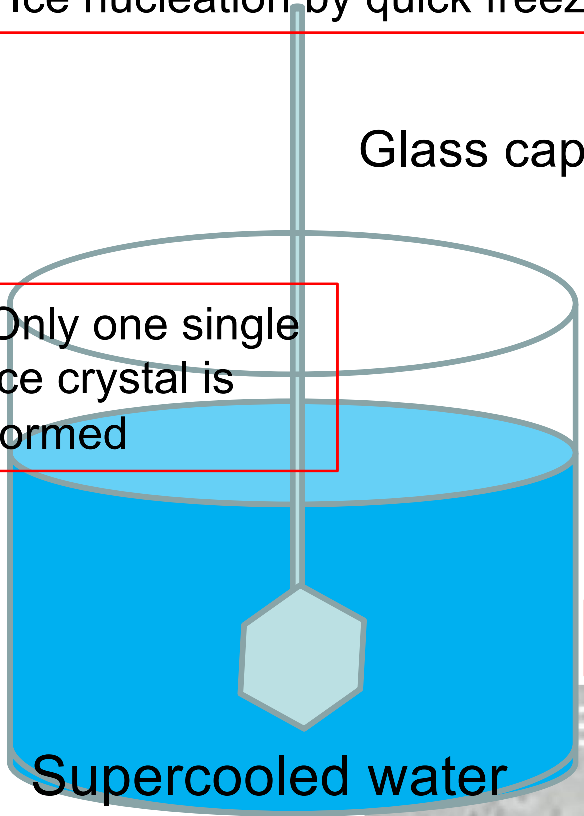
Adsorption of impurity molecules

Ice Crystal 2 project

Since the fluctuations of growth rates caused by the convection flow are always an obstacle, ISS experiments without any convection are essential to elucidate the mechanism of crystal growth.

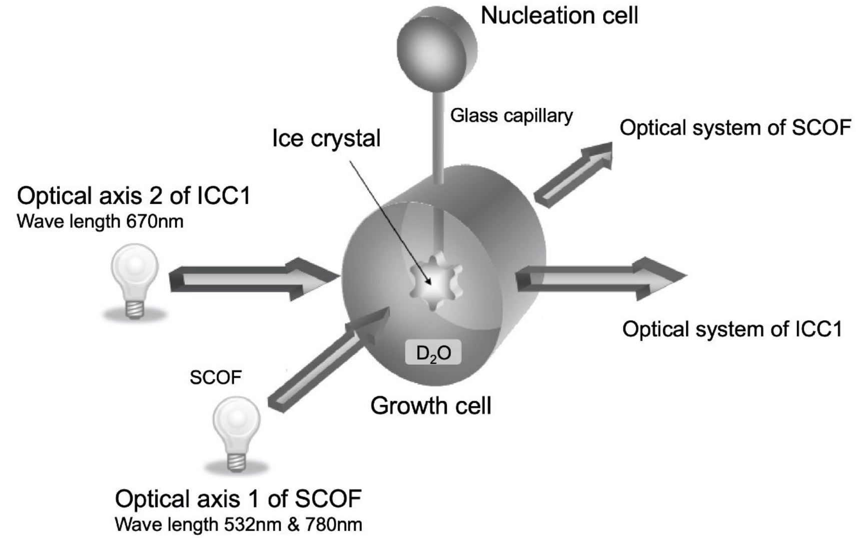
Basic idea for the free growth experiment of an ice crystal in supercooled water in space

Ice nucleation by quick freezing

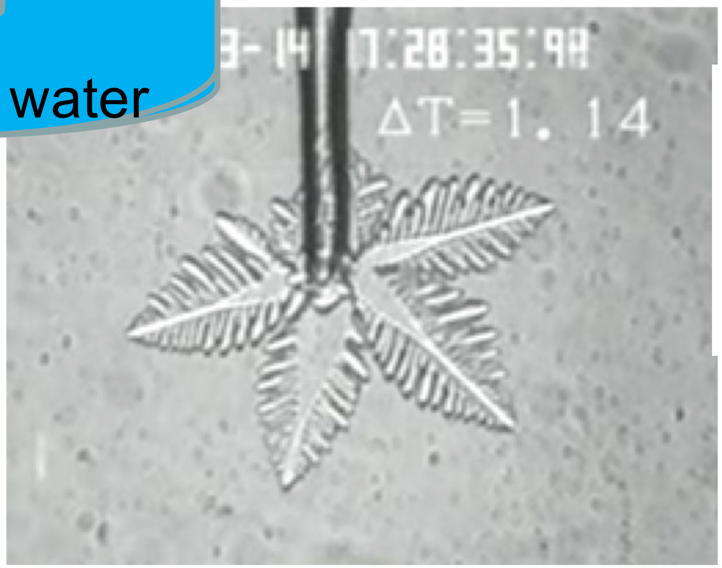


Only one single ice crystal is formed

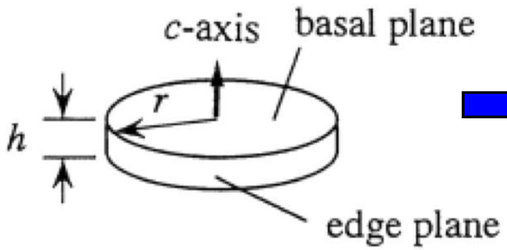
Concept of ice growth apparatus



An ice crystal at the capillary tip



Low supercooling



High supercooling

Ice Crystal Cell 1 & 2 used for both projects

Ice crystal cell 1

ISS018E044440

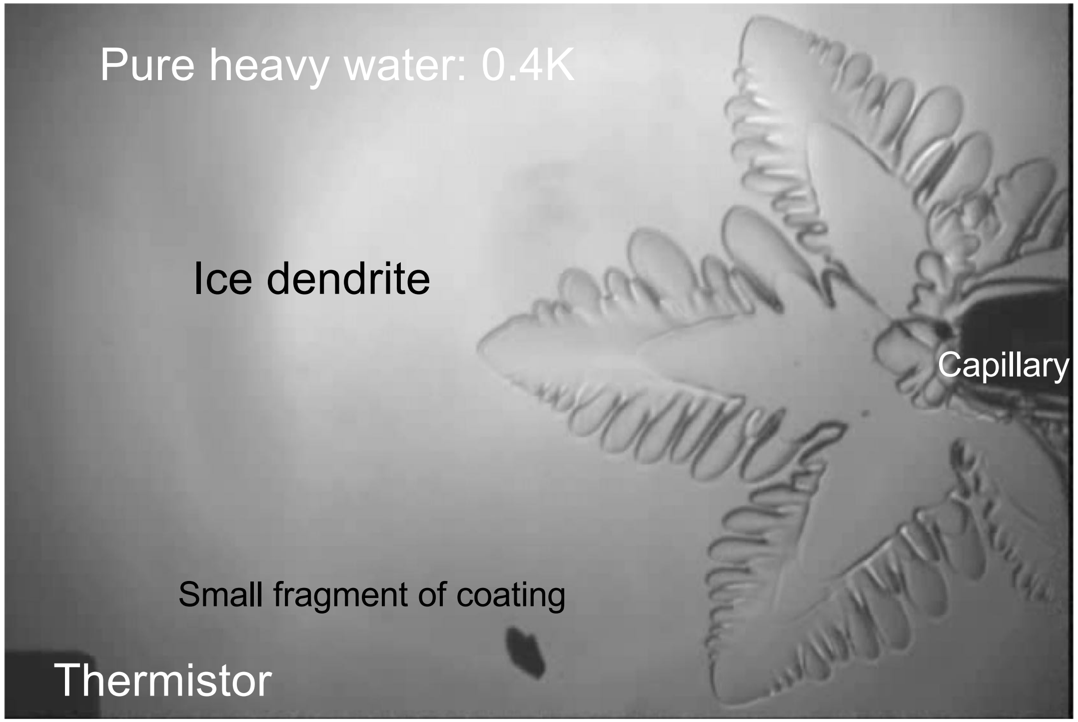
Ice crystal cell 2

- These apparatuses were launched to ISS-Kibo module and placed on the stage of the Solution Crystallization Observation Facility (SCOF).
- Ice crystal growth experiments were controlled by the telecommunication system from the ground. The growth process of an ice crystal could be observed on the ground with a few second delay.
- Ice growth experiments were repeated 100 times and more for both projects. Only the movie files were downlinked as the experimental data.

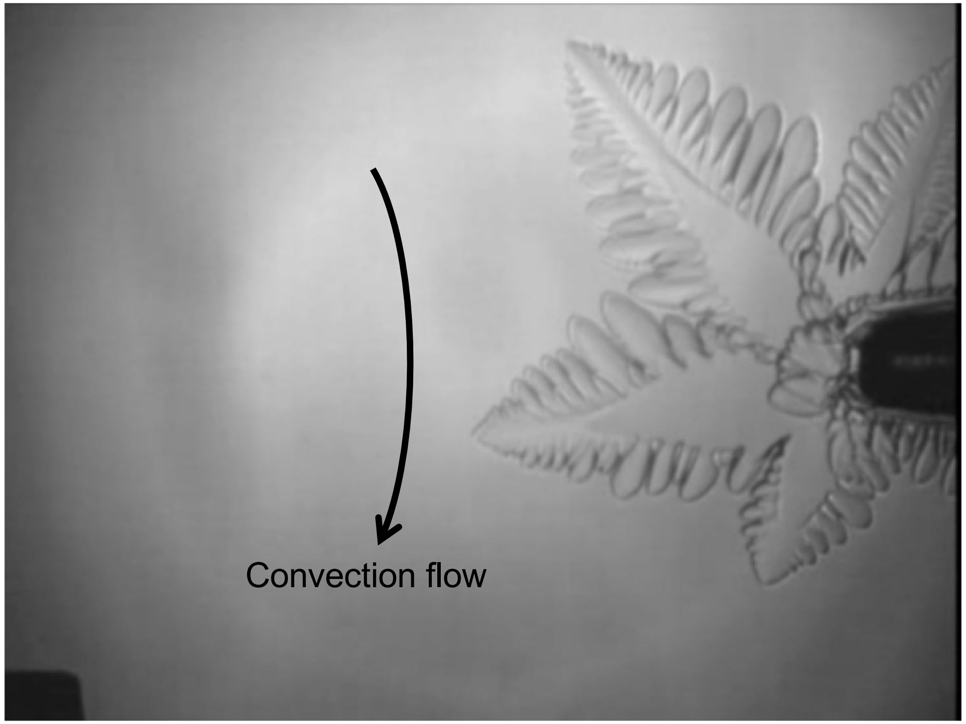
Ice Crystal 1 Project (2008-9): Pattern formation
Free growth of ice crystal in pure water

Pattern formation of ice dendrite in pure heavy water (D_2O)

In space



Ground reference



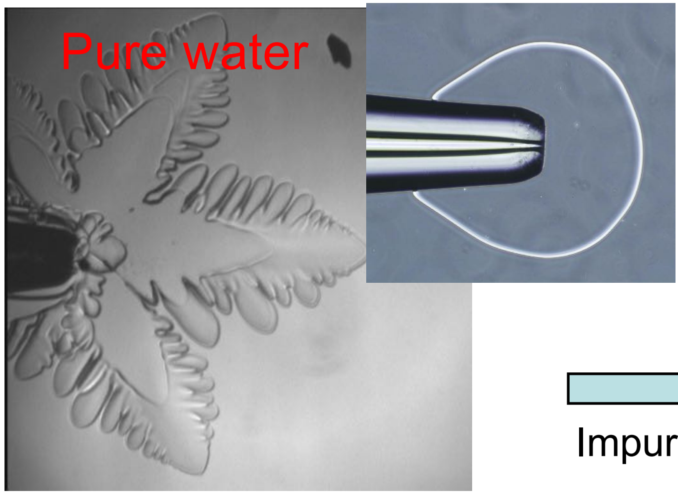
Supersymmetric dendrite pattern was formed in space!

Main results:
New model for the morphological instability and pattern formation of ice crystals

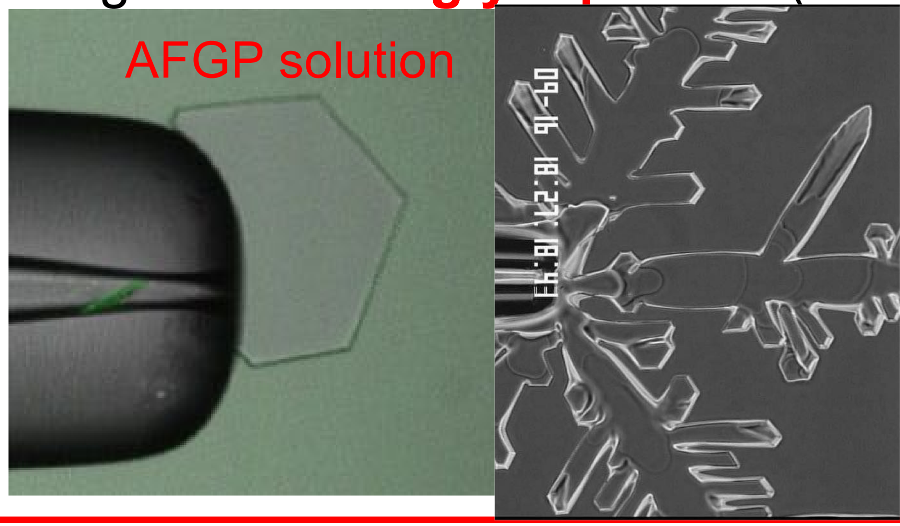
Ice crystal 2 project (2013-14): Impurity effect

Free growth of ice crystal in water with a protein impurity

Ice growth in supercooled water including **antifreeze glycoprotein** (AFGP)



Impurity effect



Polyhedral crystal patterns and step growth on both basal and pyramidal faces

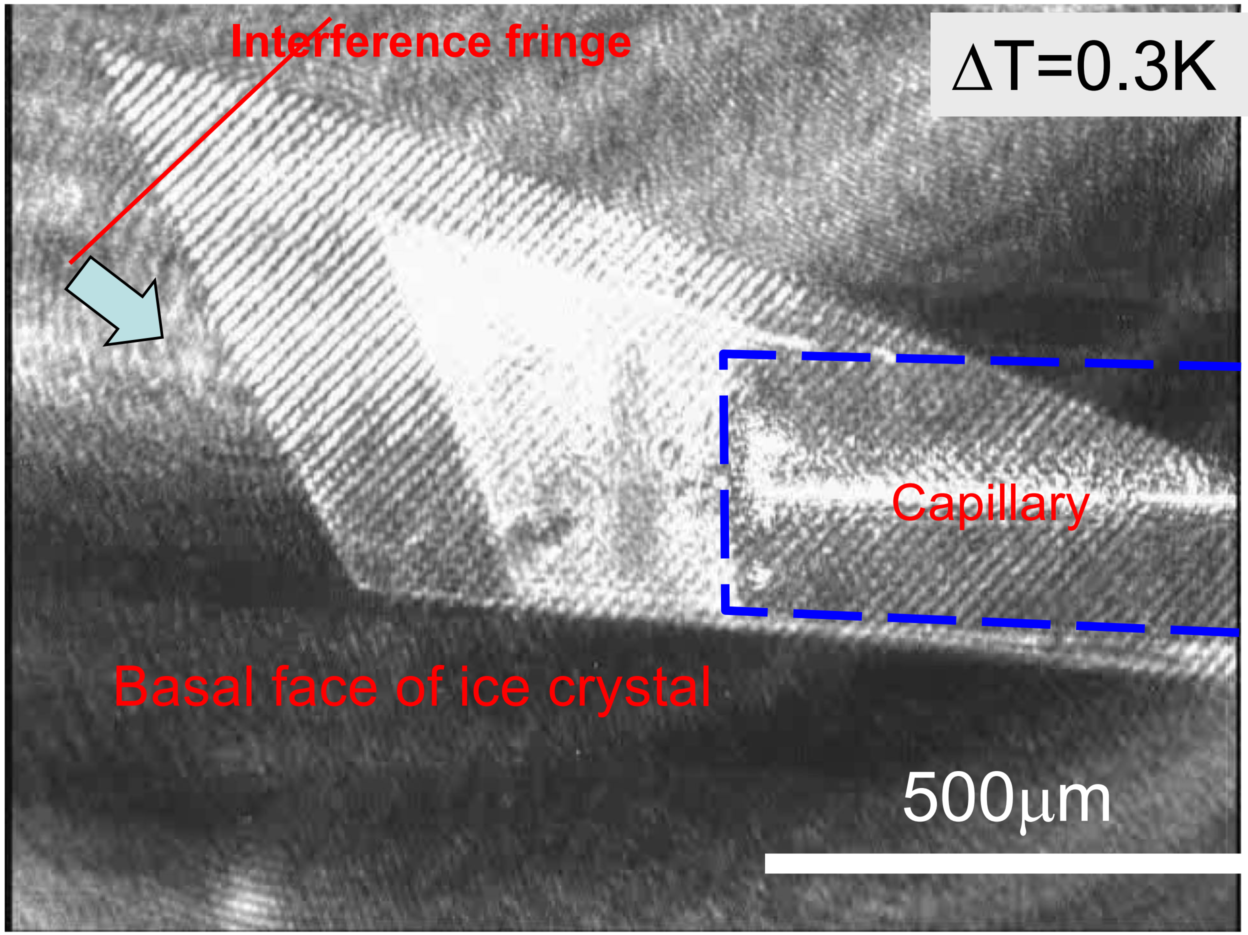
General concepts for antifreeze glycoproteins

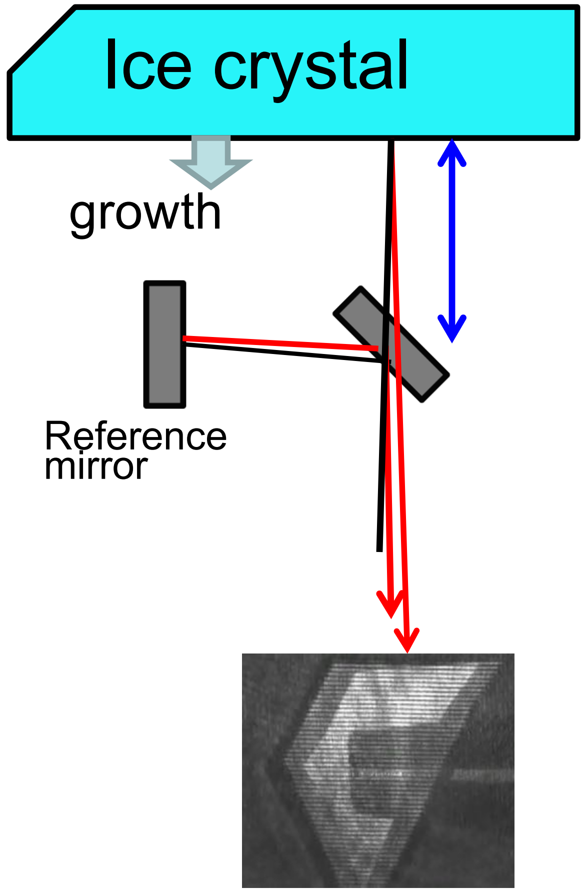
- Functional proteins to control ice crystal growth
- Included in the blood of fish living in the subfreezing sea water of Antarctic or Arctic Oceans
- Prohibit freezing their bodies under the supercooled state
- Key material for life evolution in the icy satellite of the planetary system?

Space experiments without any convection are essential to elucidate the mechanism of antifreeze function.

Interference fringe images on basal face during ice crystal growth on space

Periodic movement of interference fringes was first observed on the basal face of ice crystal in space.

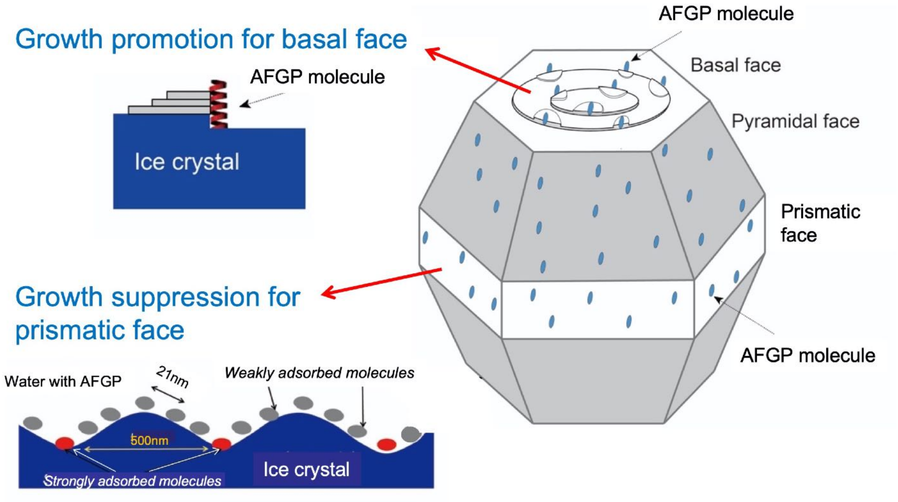




New impurity effects for crystal growth were first found by the space experiment!
Growth enhancement and Oscillatory growth

Significances for the new finding of our space experiments

Growth enhancement by impurity

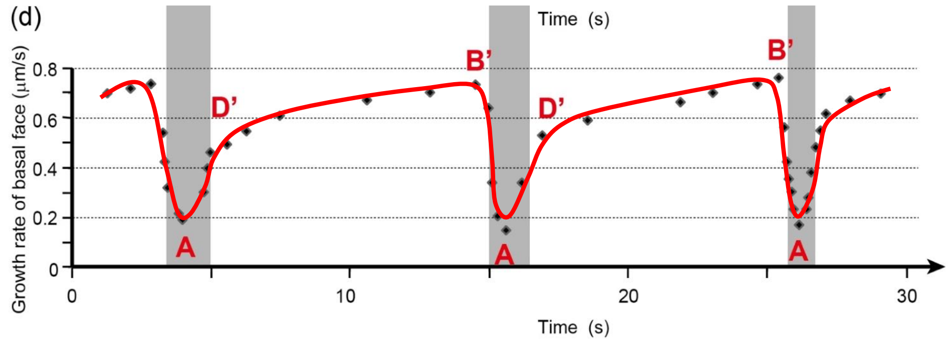


Impurities are usually considered as the factor to inhibit the crystal growth. Our space experiments first showed that the impurity of macromolecules might behave as the growth enhancement factor.

Fish living in icy sea water

Living strategy under subzero condition

Growth oscillation by impurity



Our observations gave the first direct evidence for the growth oscillation and confirmed that it occurred not by the convection flow but the kinetic process.

Agate crystal

Formation of stripe pattern in a crystal caused by oscillatory growth.

Stripe pattern (striation)

Summary

- **Two series of ice growth experiments were successfully carried out in KIBO of ISS.**
- **Patten formation mechanism for ice dendrite was precisely modeled based on the results of space experiments.**
- **New findings for the impurity effects for crystal growth based on the ISS experiments:**

  1. Growth enhancement

  2. Growth oscillation
- **These new impurity effects clarified the function of antifreeze proteins for the ice crystal. It relates to the fundamental mechanism of bio-mineralization (namely, crystal growth of inorganic materials controlled by biological macromolecules).**

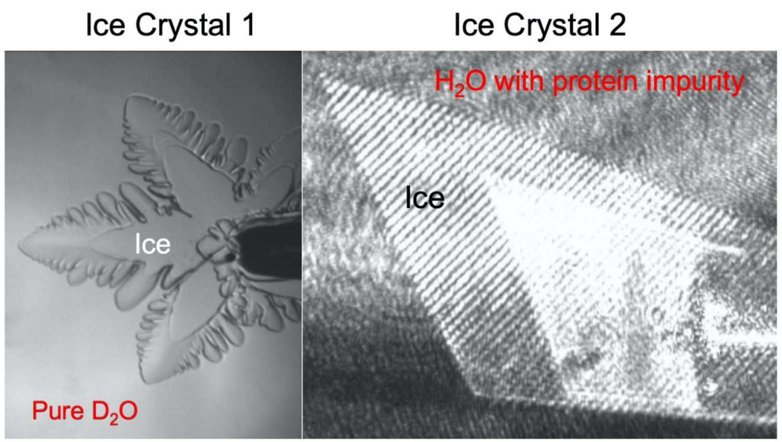
For those who are more interested

IJMSA International Journal of Microgravity Science and Application

Review paper

Ice Crystal Growth Experiments Conducted in the Kibo of International Space Station

Yoshinori FURUKAWA, Ken NAGASHIMA, Etsuro YOKOYAMA, Shunichi NAKATSUBO, Salvador ZEPEDA, Izumi YOSHIZAKI, Haruka TAMARU, Taro SHIMAOKA, Takehiko SONE, Takao MAKI, Asuka YAMAMOTO, Toshiyuki TOMOBE, Ken-ichiro MURATA and Gen SAZAKI



Ice crystals growing under microgravity conditions in ISS

Int. J. Microgravity Sci. Appl. ***38***(1) 380101 (2021); doi: 10.15011//jasma.38.380101

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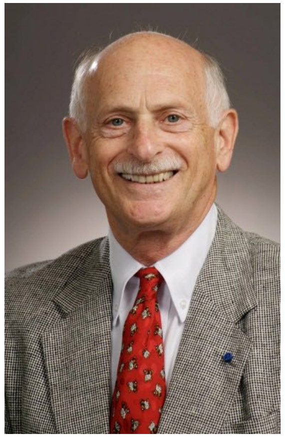

Space experiment for crystal growth

Prof. Yin Yeh
UC. Davis

Antifreeze proteins

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