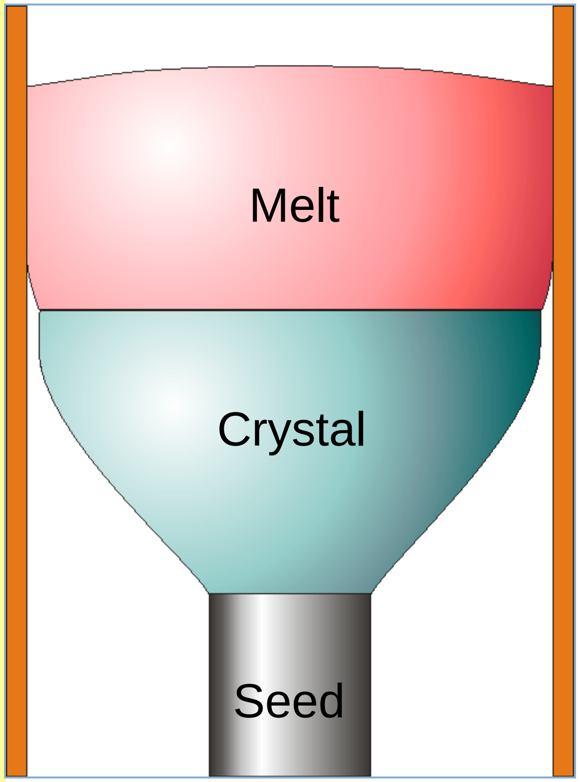
The 20th American Conference on Crystal Growth and Epitaxy (ACCGE-20)
Big Sky, Montana
August 2–7, 2015

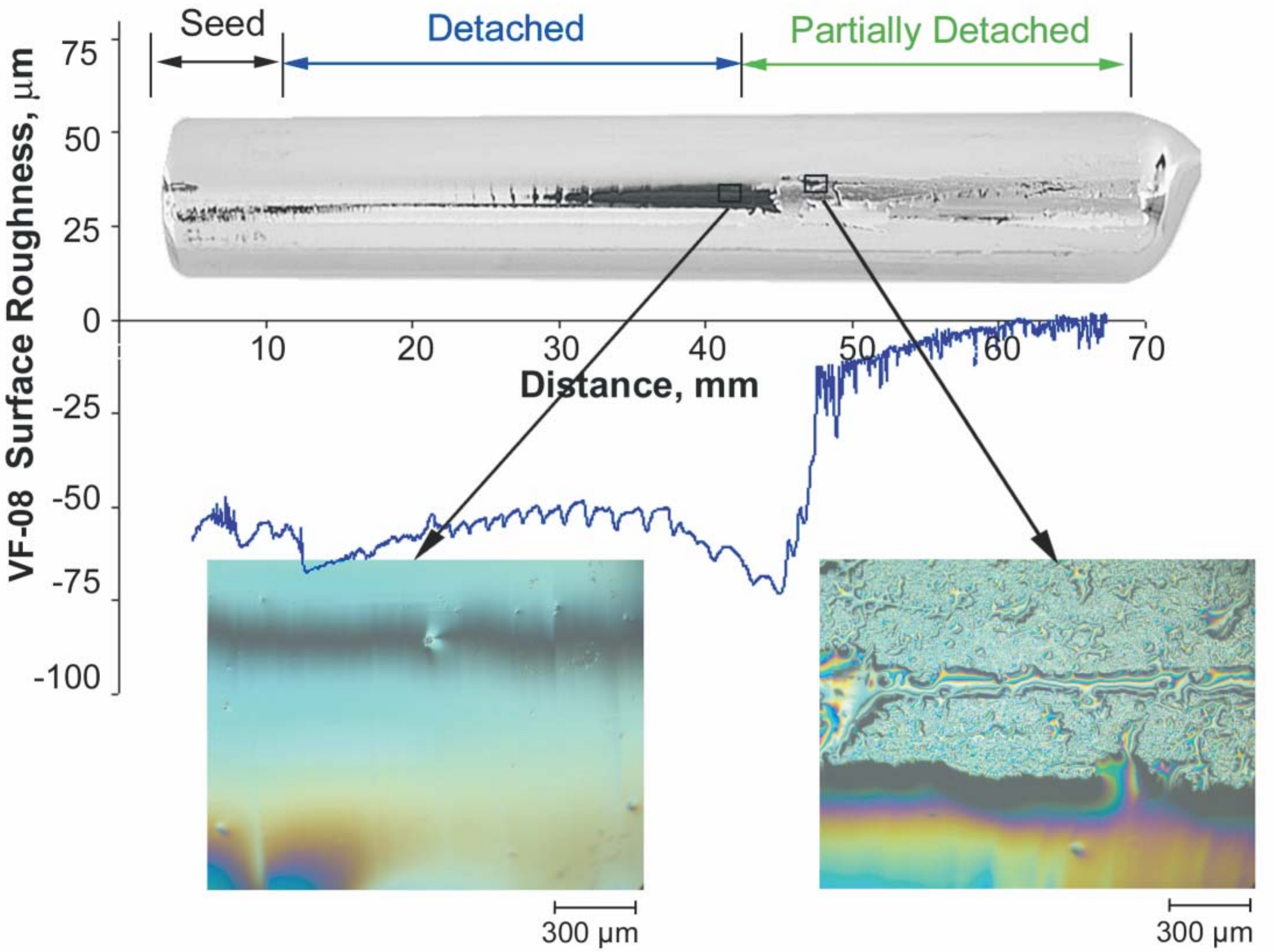
Shape Evolution of Detached Bridgman Crystals Grown in Microgravity

Research Motivation

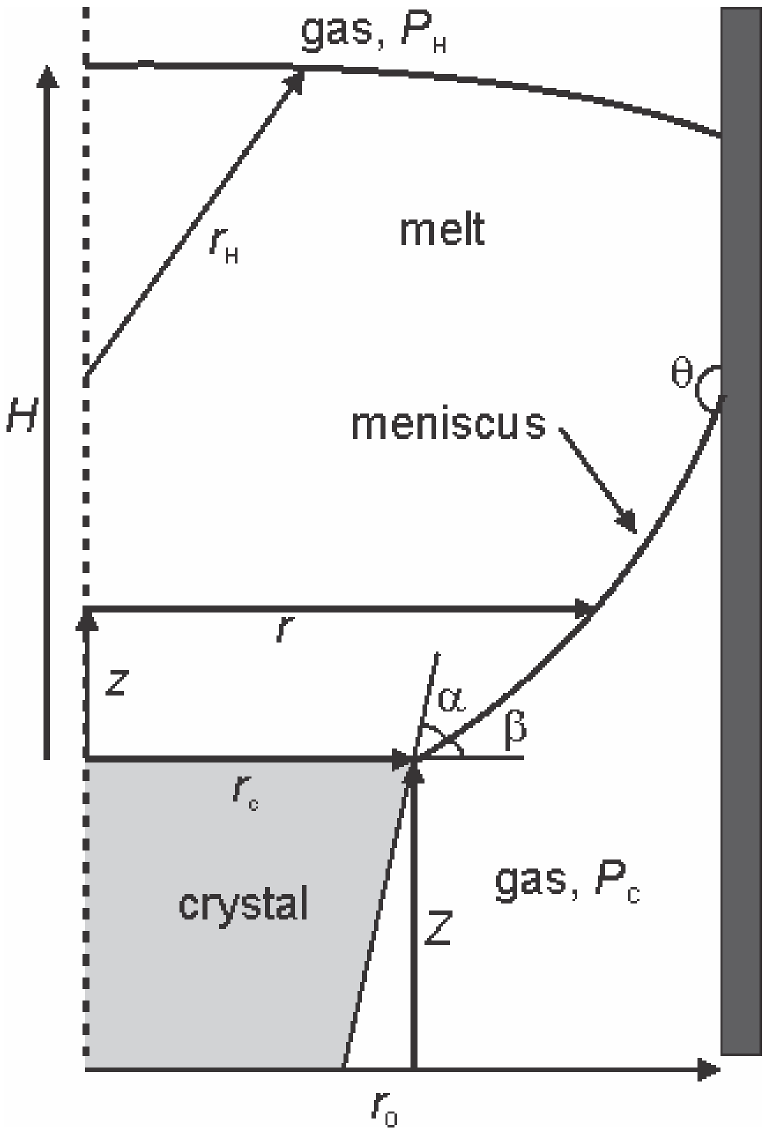
- What are the conditions for detachment in microgravity and how do they depend on the governing parameters?
  - Growth angle
  - Contact angle
  - Pressure differential
  - Bond number (ratio of gravity to capillarity)
- Which detached growth solutions are dynamically stable?
- How does an initial crystal radius evolve to one of the following states?
  - Stable detached gap
  - Attachment to the crucible wall
  - Meniscus collapse
- What are the effects of angular dependence on the crystal shape (faceting effects)?



Detached Crystal Growth



Schematic Diagram of Detached Solidification



α: growth angle
θ: contact or wetting angle
$\Delta P = P_H - P_C$: Dimensionless pressure differential across the meniscus
$z(r)$: meniscus shape
$Z(r)$: crystal shape

$$\Delta P = \Delta P_{external} + \rho g h + 2\frac{\gamma}{r_{tm}}$$

where

$\Delta P_{external}$: external gas pressure differential

$\rho g h$: weight of melt (pressure head)

$2\frac{\gamma}{r_{tm}}$: capillary pressure from top meniscus

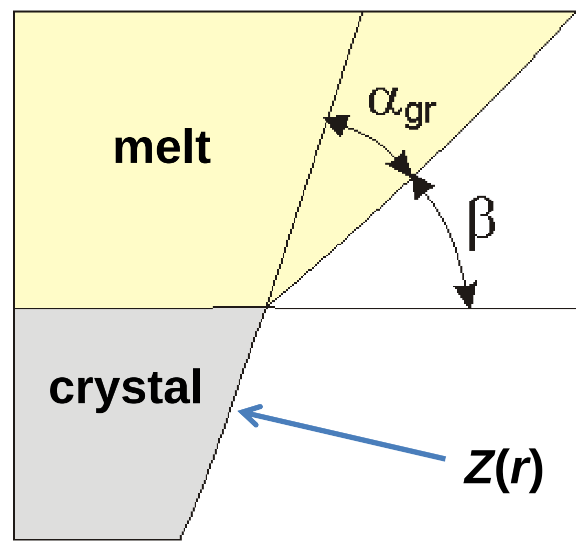
Equations in Zero Gravity

$$\frac{\partial z}{\partial r} = \pm \frac{\Delta P(r^2 - 1) - 2\cos\theta}{\sqrt{4r^2 - (\Delta P(r^2-1) - 2\cos\theta)^2}}$$

Meniscus shape equation, *z*(*r*): 2 possible solutions for *g* = 0, *B* = 0

$$\frac{dZ}{dr} = \tan(\alpha + \beta)$$

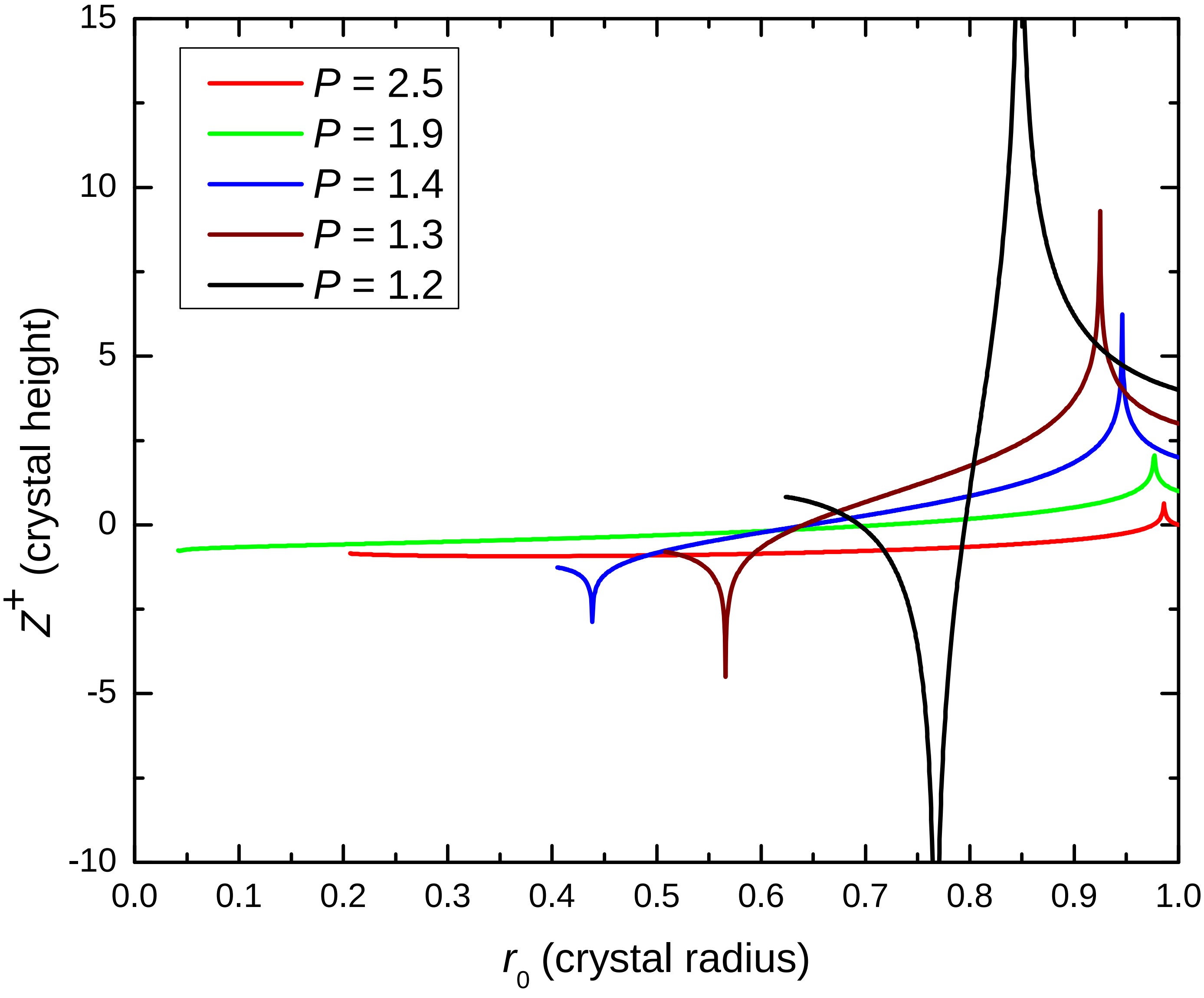
Crystal shape equation, *Z*(*r*): 2 possible solutions in zero gravity



$$\frac{dZ^{\pm}}{dr} = \frac{\sqrt{4r^2 - y^2}\tan\alpha \pm y}{\sqrt{4r^2 - y^2} \mp y\tan\alpha}, \qquad y = \Delta P(r^2 - 1) - 2\cos\theta$$

Crystal Evolution for $\theta + \alpha > 180°$; Z^+ solution

Ge
α= 14.3°
θ= 172°

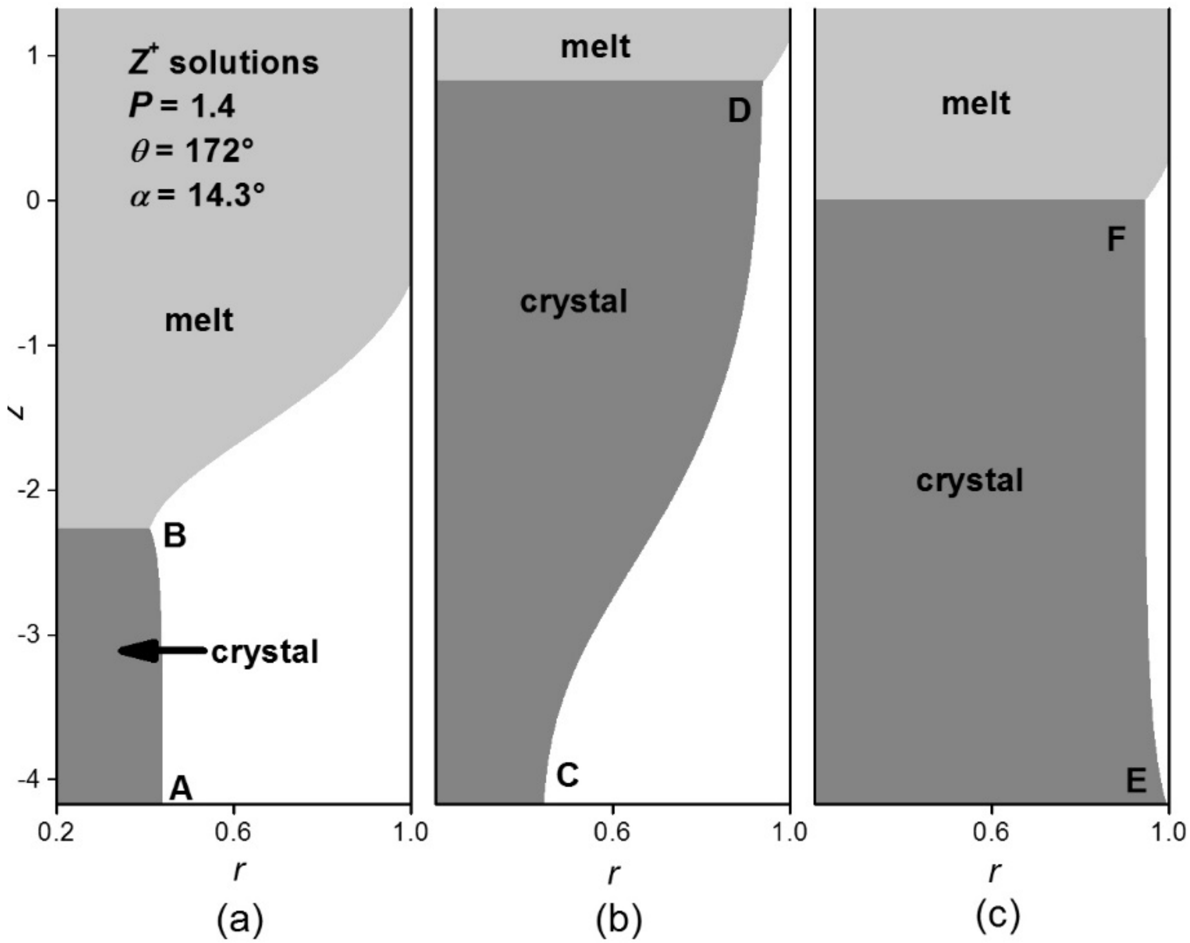


Ge Crystal Evolution for $\theta + \alpha > 180°$; Z^+ solution

Material: Ge
Growth Angle: 14.3°
Contact Angle: 172°
ΔP = 1.4

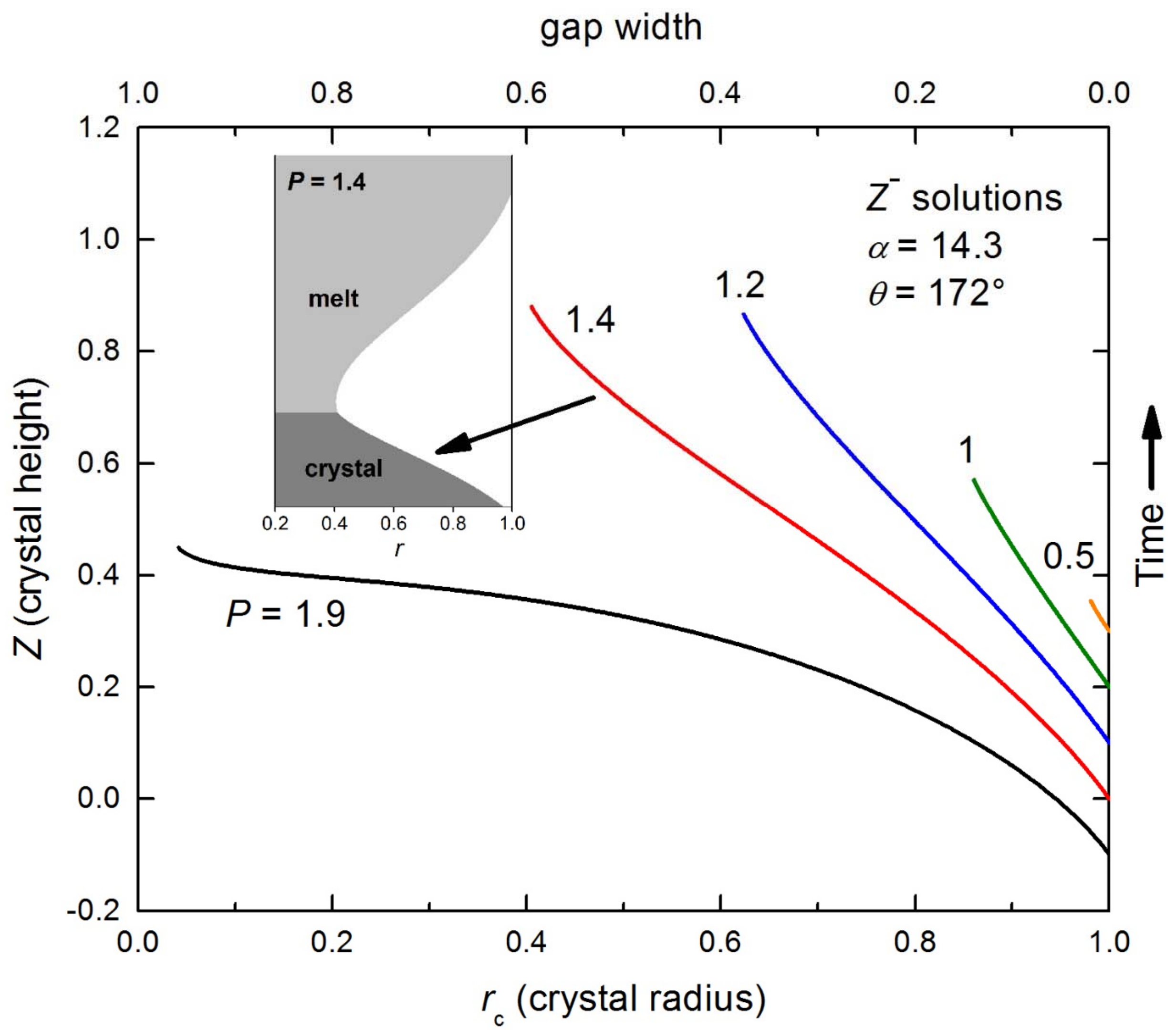
(a) Radius decreases until meniscus collapses

(b, c) Radius increases or decreases until stable growth with a constant radius is reached



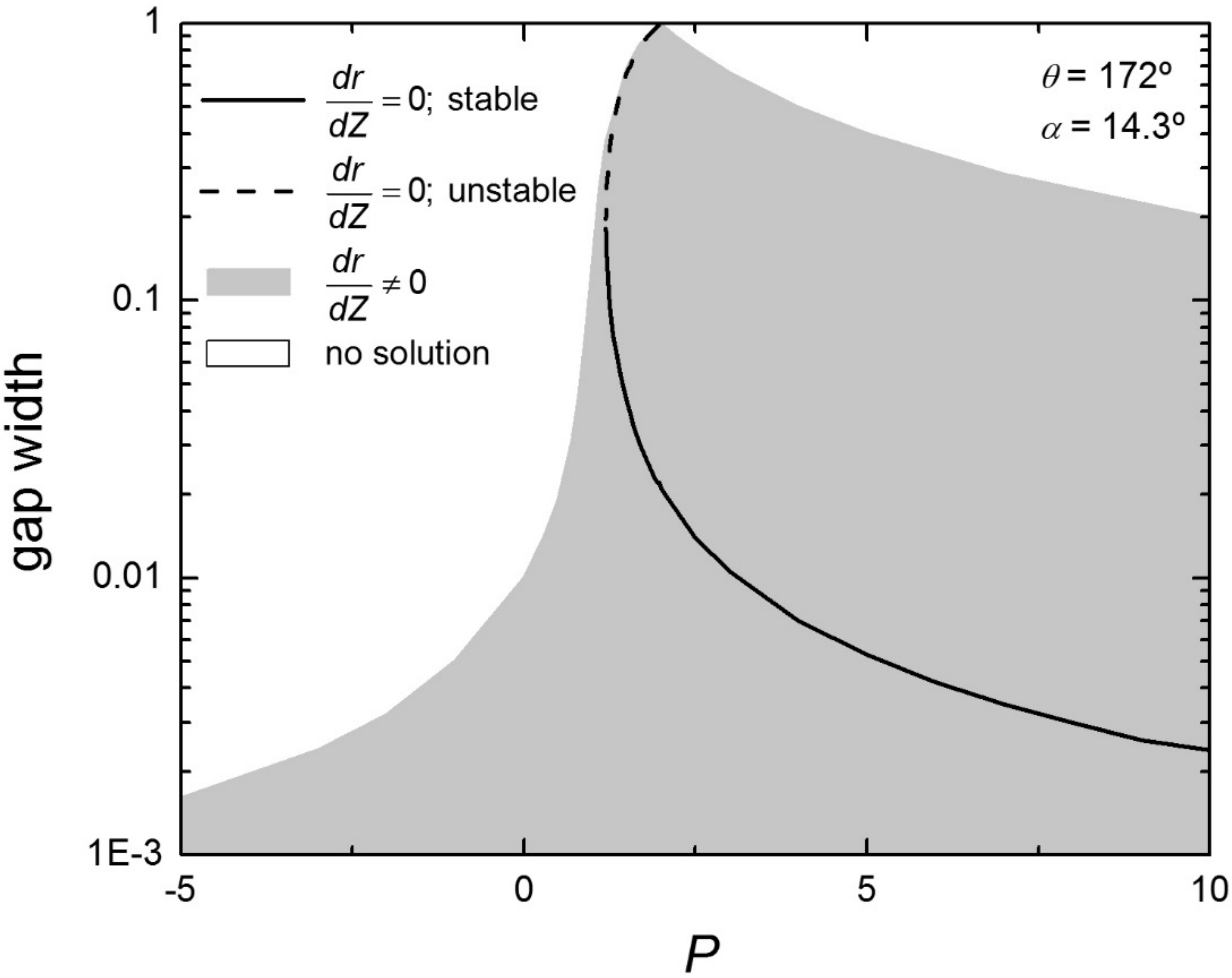
Ge Crystal Evolution for $\theta + \alpha > 180°$; Z^- solution

Material: Ge
Growth Angle: 14.3°
Contact Angle: 172°



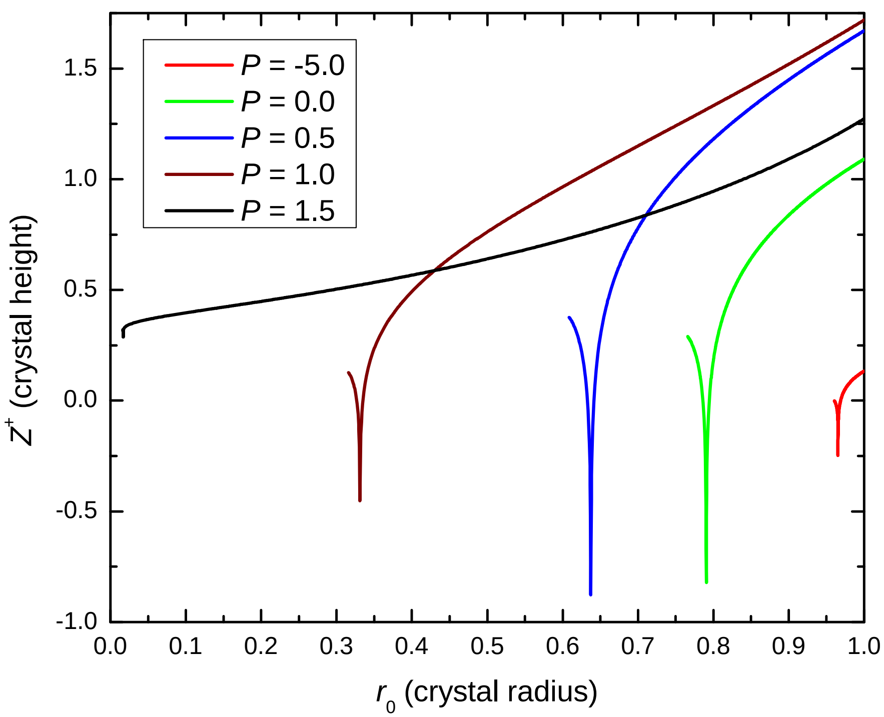
For Z^- solutions, all crystals decrease in radius until the menisci collapse

Existence Region for $\theta + \alpha > 180°$

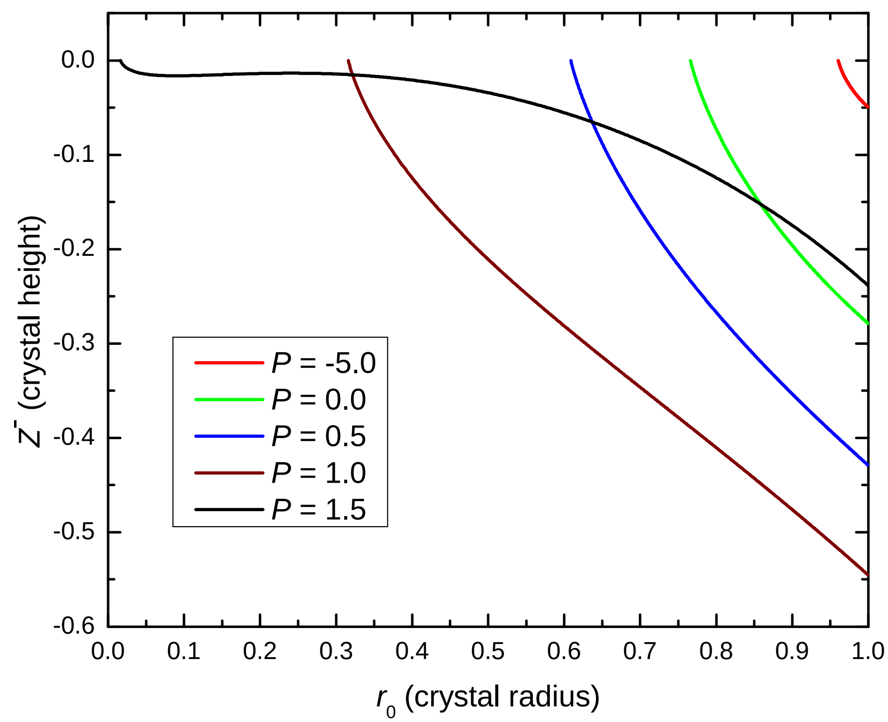


Crystal Evolution for $\theta + \alpha < 180°$

Z^+ solutions



Z^- solutions



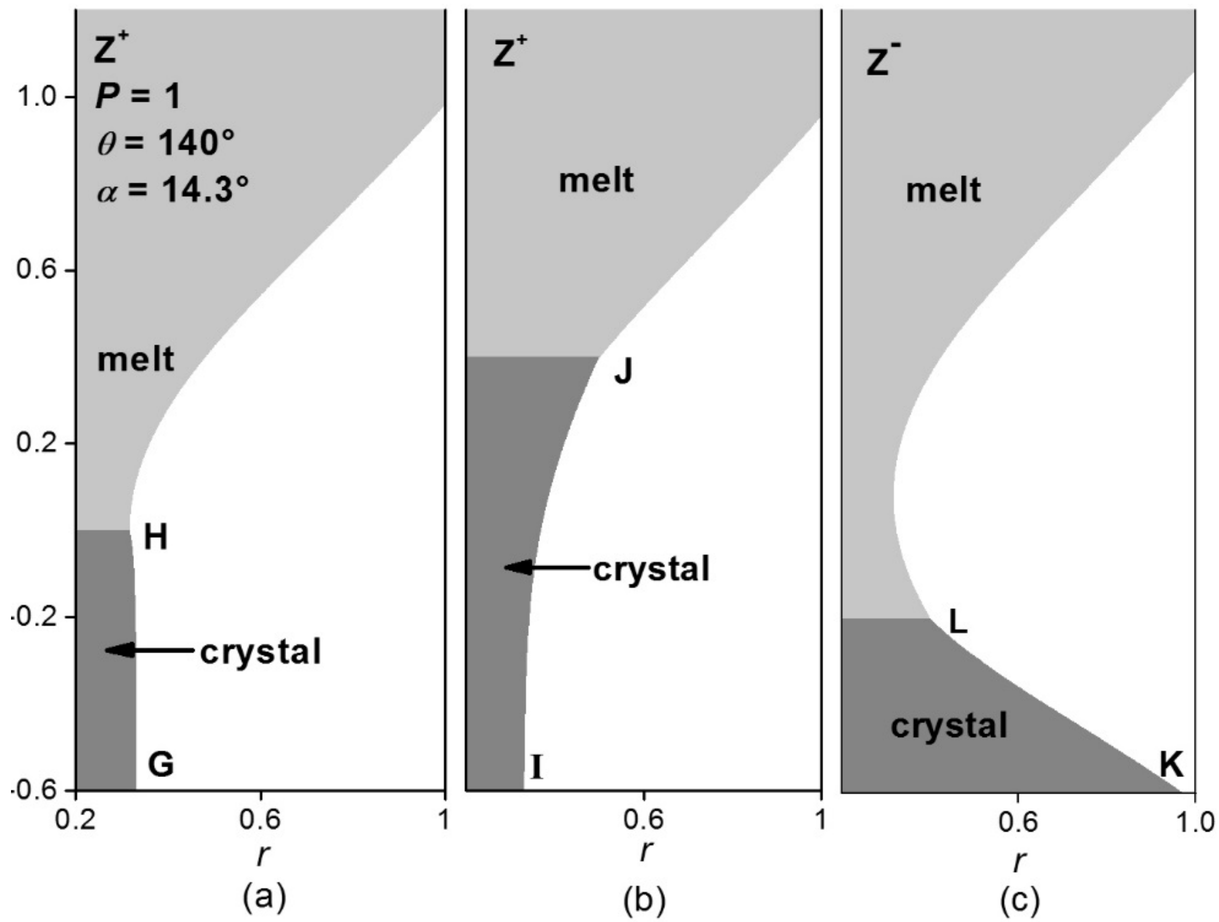
$\alpha = 14.3°$; $\theta = 140°$

Crystal Evolution for $\theta + \alpha < 180°$

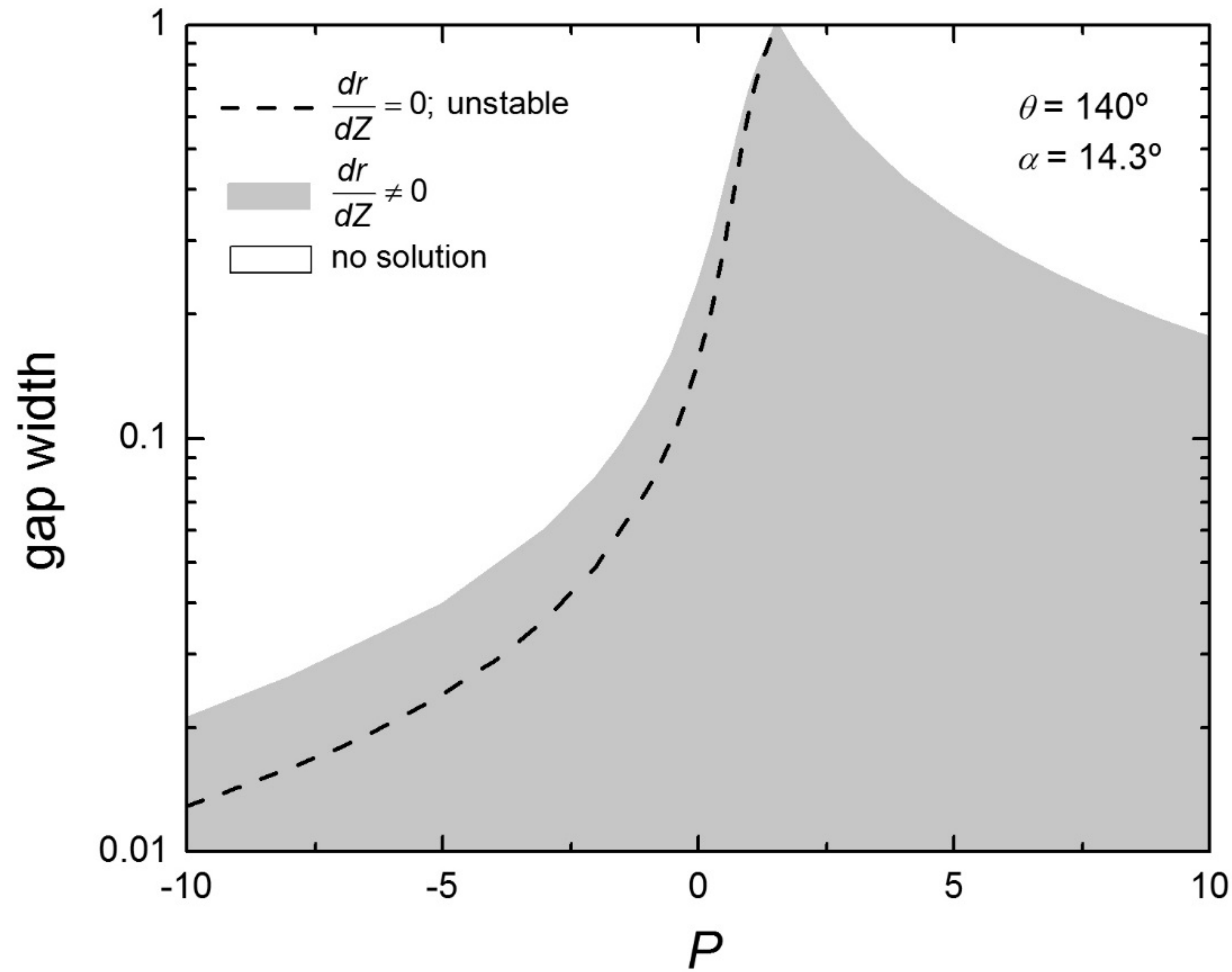
Material: Ge
Growth Angle: 14.3°
Contact Angle: 140°
ΔP = 1.0

(a, c) Radius decreases until meniscus collapses

(b) Radius increases or decreases until attachment at the crucible wall



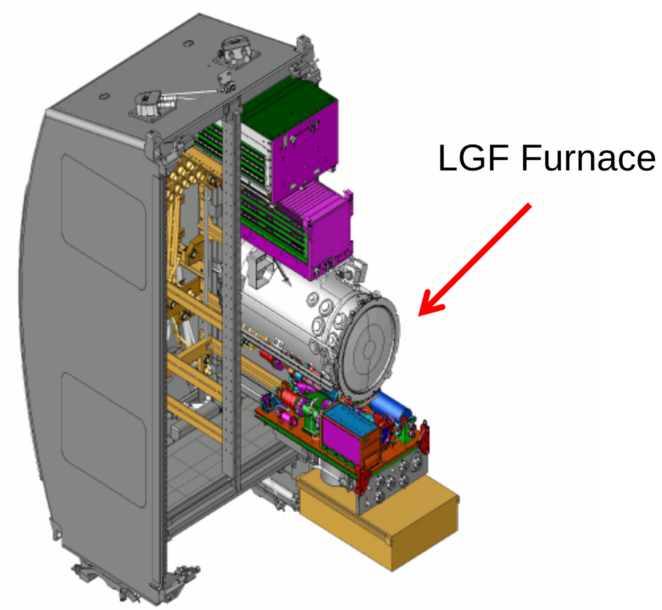
Existence Region for $\theta + \alpha < 180°$



ICESAGE Flight Investigation

- “Influence of Containment on the Growth of Silicon-Germanium” (ICESAGE) is a collaborative investigation between NASA and the European Space Agency (ESA)
- The ICESAGE experiments will be conducted in the Low Gradient Furnace (LGF) in the Materials Science Laboratory on the International Space Station (ISS)

- ICESAGE will test the theories of crystal shape evolution in detached Bridgman growth
- Dependence on the parameters ΔP, θ, and the crystal starting position r_0 will be examined
- Launch is currently planned on a SpaceX flight in 2016



Materials Science Laboratory

Summary

- A theory describing the shape evolution of detached Bridgman crystals in microgravity has been developed
- A starting crystal of initial radius r_0 will evolve to one of the following states:
  - Stable detached gap
  - Attachment to the crucible wall
  - Meniscus collapse
- Only crystals where $\alpha + \theta > 180°$ will achieve stable detached growth in microgravity
- Results of the crystal shape evolution theory are consistent with predictions of the dynamic stability of crystallization (Tatarchenko, *Shaped Crystal Growth*, Kluwer, 1993)
- Tests of transient crystal evolution are planned for ICESAGE, a series of Ge and GeSi crystal growth experiments planned to be conducted on the ISS