Highly porous nature of a primitive asteroid revealed by thermal imaging

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Hayabusa2 TIR Team, Joint Science Team, & Project Team

Article

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Tatsuaki Okada[1,2]✉, Tetsuya Fukuhara[3], Satoshi Tanaka[1,4,5], Makoto Taguchi[3], Takehiko Arai[6], Hiroki Senshu[7], Naoya Sakatani[1], Yuri Shimaki[1], Hirohide Demura[8], Yoshiko Ogawa[8], Kentaro Suko[8], Tomohiko Sekiguchi[9], Toru Kouyama[10], Jun Takita[11], Tsuneo Matsunaga[12], Takeshi Imamura[5], Takehiko Wada[1], Sunao Hasegawa[1], Jörn Helbert[13], Thomas G. Müller[14], Axel Hagermann[15], Jens Biele[16], Matthias Grott[13], Maximilian Hamm[13,17], Marco Delbo[18], Naru Hirata[8], Naoyuki Hirata[19], Yukio Yamamoto[1,4], Seiji Sugita[2], Noriyuki Namiki[4,20], Kohei Kitazato[8], Masahiko Arakawa[19], Shogo Tachibana[1,2], Hitoshi Ikeda[21], Masateru Ishiguro[22], Koji Wada[7], Chikatoshi Honda[8], Rie Honda[23], Yoshiaki Ishihara[12], Koji Matsumoto[4,20], Moe Matsuoka[1], Tatsuhiro Michikami[24], Akira Miura[1], Tomokatsu Morota[2], Hirotomo Noda[20], Rina Noguchi[1], Kazunori Ogawa[19,25], Kei Shirai[19], Eri Tatsumi[2,26], Hikaru Yabuta[27], Yasuhiro Yokota[1], Manabu Yamada[7], Masanao Abe[1,4], Masahiko Hayakawa[1], Takahiro Iwata[1,4], Masanobu Ozaki[1,4], Hajime Yano[1,4], Satoshi Hosoda[1], Osamu Mori[1], Hirotaka Sawada[1], Takanobu Shimada[1], Hiroshi Takeuchi[1,4], Ryudo Tsukizaki[1], Atsushi Fujii[1], Chikako Hirose[21], Shota Kikuchi[1], Yuya Mimasu[1], Naoko Ogawa[1,25], Go Ono[21], Tadateru Takahashi[1,29], Yuto Takei[1], Tomohiro Yamaguchi[1,30], Kent Yoshikawa[21], Fuyuto Terui[1], Takanao Saiki[1], Satoru Nakazawa[1], Makoto Yoshikawa[1,4], Seiichiro Watanabe[1,28] & Yuichi Tsuda[1,4]

[1]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan. [2]University of Tokyo, Tokyo, Japan. [3]Rikkyo University, Tokyo, Japan. [4]The Graduate University for Advanced Studies, SOKENDAI, Hayama, Japan. [5]University of Tokyo, Kashiwa, Japan. [6]Ashikaga University, Ashikaga, Japan. [7]Planetary Exploration Research Center, Chiba Institute of Technology, Narashino, Japan. [8]University of Aizu, Aizu-Wakamatsu, Japan. [9]Hokkaido University of Education, Asahikawa, Japan. [10]National Institute of Advanced Industrial Science and Technology (AIST), Tokyo, Japan. [11]Hokkaido Kitami Hokuto High School, Kitami, Japan. [12]National Institute for Environmental Studies (NIES), Tsukuba, Japan. [13]German Aerospace Center (DLR), Berlin, Germany. [14]Max-Planck Institute for Extraterrestrial Physics, Garching, Germany. [15]University of Stirling, Stirling, UK. [16]German Aerospace Center (DLR), Cologne, Germany. [17]University of Potsdam, Potsdam, Germany. [18]Universite Cote d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France. [19]Kobe University, Kobe, Japan. [20]National Astronomical Observatory of Japan (NAOJ), Mitaka, Japan. [21]Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan. [22]Seoul National University, Seoul, South Korea. [23]Kochi University, Kochi, Japan. [24]Kindai University, Higashi-Hiroshima, Japan. [25]Space Exploration Center, Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan. [26]Instituto de Astrofísica de Canarias, University of La Laguna, La Laguna, Tenerife, Spain. [27]Hiroshima University, Higashi-Hiroshima, Japan. [28]Nagoya University, Nagoya, Japan. [29]Present address: NEC Corporation, Fuchu, Japan. [30]Present address: Mitsubishi Electric Corporation, Kamakura, Japan. ✉e-mail: okada@planeta.sci.isas.jaxa.jp

Abstract

- Carbonaceous (C)-type asteroids are relics of the early Solar System that have preserved primitive materials since their formation ~4.6 billion years ago.
- They are probably analogues of C-chondrites and are essential for understanding planetary formation processes.
- However, their physical properties remain poorly known, because C-chondrite meteoroids tend not to survive entry to Earth's atmosphere.
- Here we report on global one-rotation thermal images of Ryugu (C-type) taken by TIR , indicating that the asteroid's boulders and their surroundings have similar temperatures, with a derived very low thermal inertia (TI) of ~300 J m^{-2} $s^{-0.5}$ K^{-1} (tiu).
- Contrary to predictions that the surface consists of regolith and dense boulders, this low TI suggests that the boulders are more porous than typical C-chondrites and that their surroundings are covered with porous fragments of > 10 cm in diameter.
- Close-up thermal images confirmed the presence of such porous fragments and the flat diurnal temperature profiles suggest a strong surface roughness effect.
- We also observed boulders during the day in the close-up thermal images, with TI > 600 tiu, corresponding to dense boulders similar to typical C-chondrites.
- These results constrain the formation history of Ryugu: the asteroid must be a rubble pile formed from impact fragments of a parent body with micro-porosity of ~30 to 50 % that experienced a low degree of consolidation.
- The dense boulders might have originated from the consolidated innermost region or they may have an exogenic origin.
- This low-porosity asteroid may link cosmic fluffy dust to dense celestial bodies.

Abstract (Summary)

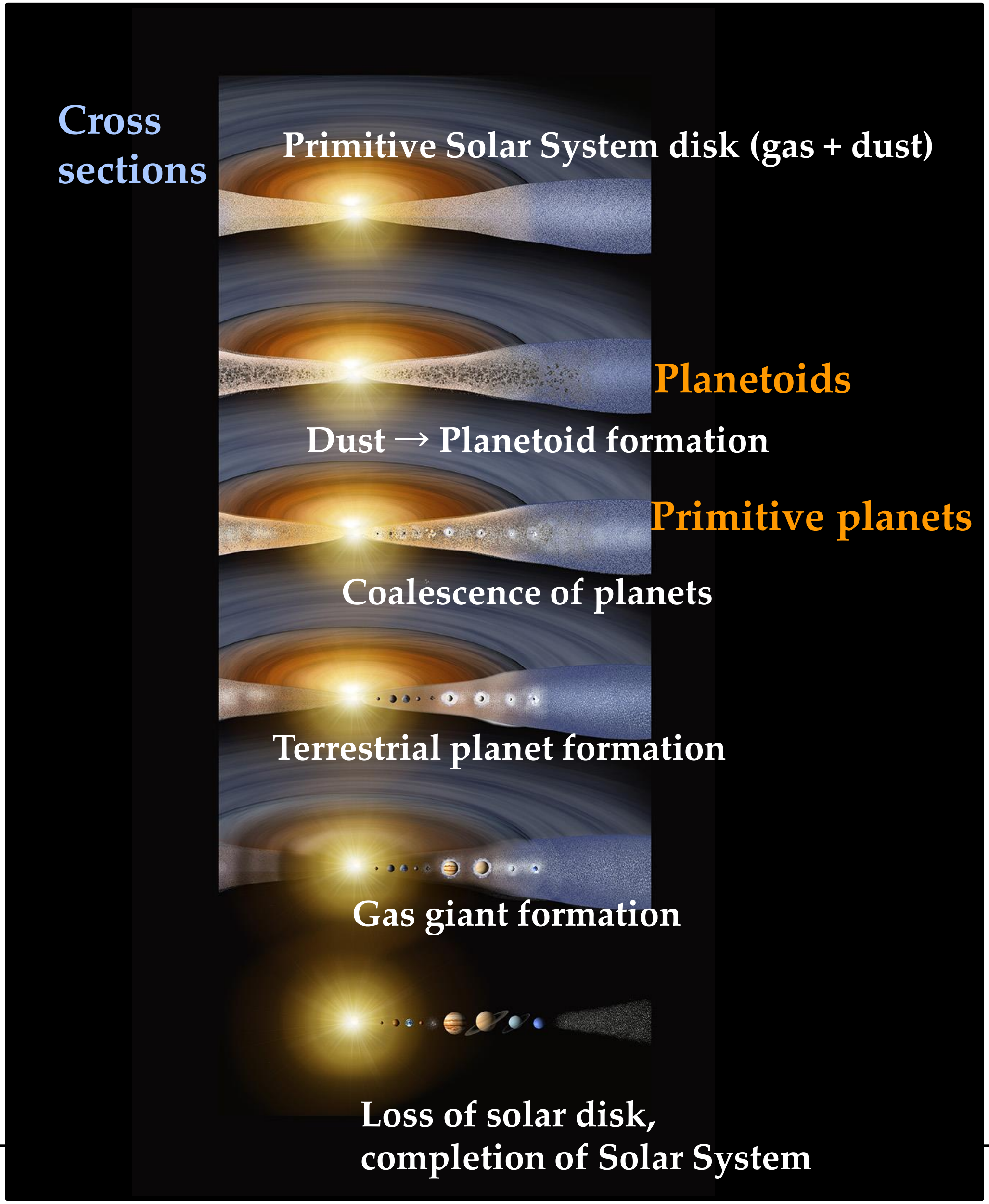
- Carbonaceous (C)-type asteroids:
  - Primitive materials of early solar system
  - Likely analogues of C-chondrites enriched in volatiles (water, organics)
  - Essential for understanding planetary formation
  - Physical properties poorly known.
- Thermography of Ryugu (C-type asteroid) by TIR:
  - The first global one-rotation thermal images of an asteroid in history!
  - The first high-resolution and close-up thermal images of an asteroid surface as well!
- <u>Surprises!!</u>
  - Similar temperatures between boulders and their surroundings, indicating same materials
  - Highly porous materials indicated by their very low thermal inertia (TI) of ~300 J m^{-2} $s^{-0.5}$ K^{-1} (tiu), Cf. typical TI of C-chondrites: 600-1000 tiu.
  - Surroundings are NOT covered with regolith but with >10 cm-sized porous fragments
  - Flat diurnal temperature profiles suggesting a strong surface roughness effect.
  - Discovery of cold boulders "Cold Spots" with TI > 600 tiu, typical dense C-chondrites.
- New Formation scenario of Ryugu:
  - Ryugu must be a rubble pile formed from impact fragments of a porous parent body
  - Materials have never experienced substantial consolidation or compaction.
  - Dense boulders from the more consolidated core of the parent body or an exogenic origin.
- This low-porosity asteroid may link cosmic fluffy dust to dense celestial bodies.

Highlights of this paper

- ◆ The first set of high-resolution, one-rotation global thermal images of an asteroid in history.
- ◆ Discovery of asteroid surface dominated by highly porous boulders, except for dense rocks as “cold spots”.
- ◆ Flat diurnal temperature profiles mainly caused by surface roughness, implying to the cometary nucleus.
- ◆ Asteroid formation scenario updated: primitive small bodies including planetesimals may not have experienced substantial compaction – hypothesizing a link from fluffy dust to dense celestial bodies.

Hayabusa2 Science:
Elucidating the birth and evolution of the Solar System

Ref: from Hayabusa2 fact sheet



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Topics

① Investigating the materials that formed the planets

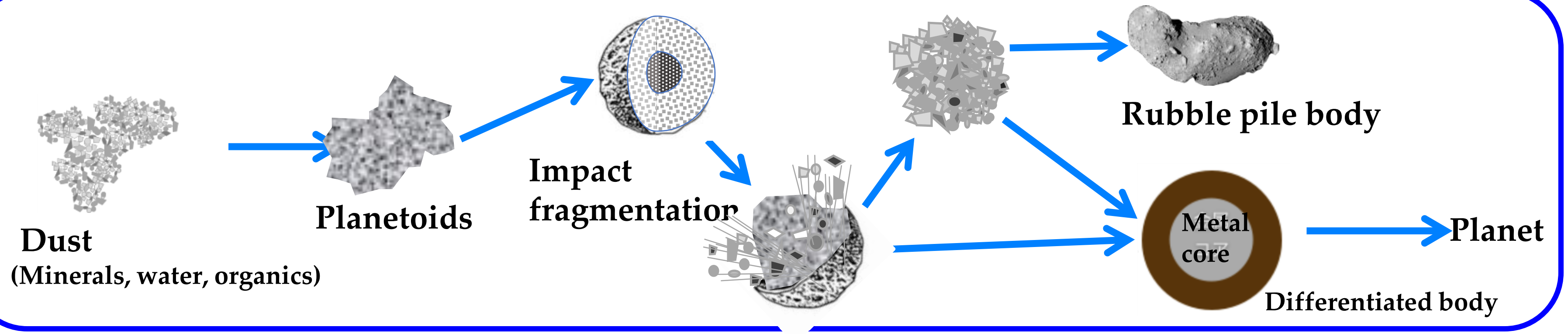
What materials existed in the primitive Solar System disk, and how did they change up to the formation of planets?

② Investigating the formation processes of the planets

How do celestial bodies grow from planetoids to planets?

Investigating planetary formation

Ref: from Hayabusa2 fact sheet



(© JAXA)

- Elucidate the structure of planetoids that eventually became planets.
- Elucidate what processes occurred during the collisions, coalescence, and accumulation of celestial bodies.

↓

<u>Elucidate formation processes from planetoid to planet</u>

Keywords:

- Rubble pile body: A celestial body formed from accumulated rubble
- Impacts and coalescence: When celestial bodies collide, the resulting fragments can combine to form a new body
- Accumulation: Accumulation of fragments resulting from a collision via the force of gravity

Fig.1 Global Thermal Images: Geologic Features

- All of the major geologic features identifiable.
- Comparable to the asteroid shape model (seen even in the night)
- Warmer in the Southern hemisphere due to the summer..

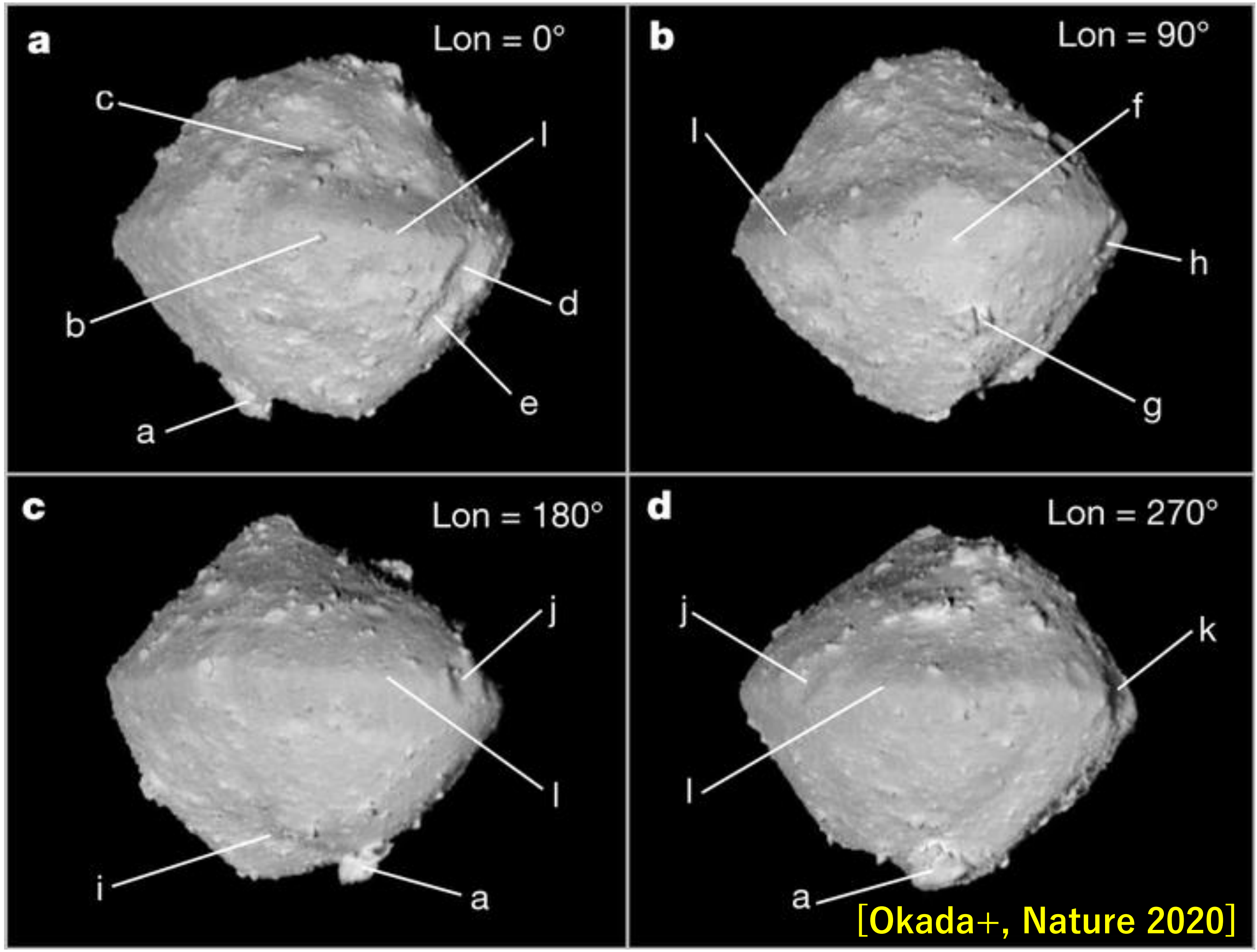


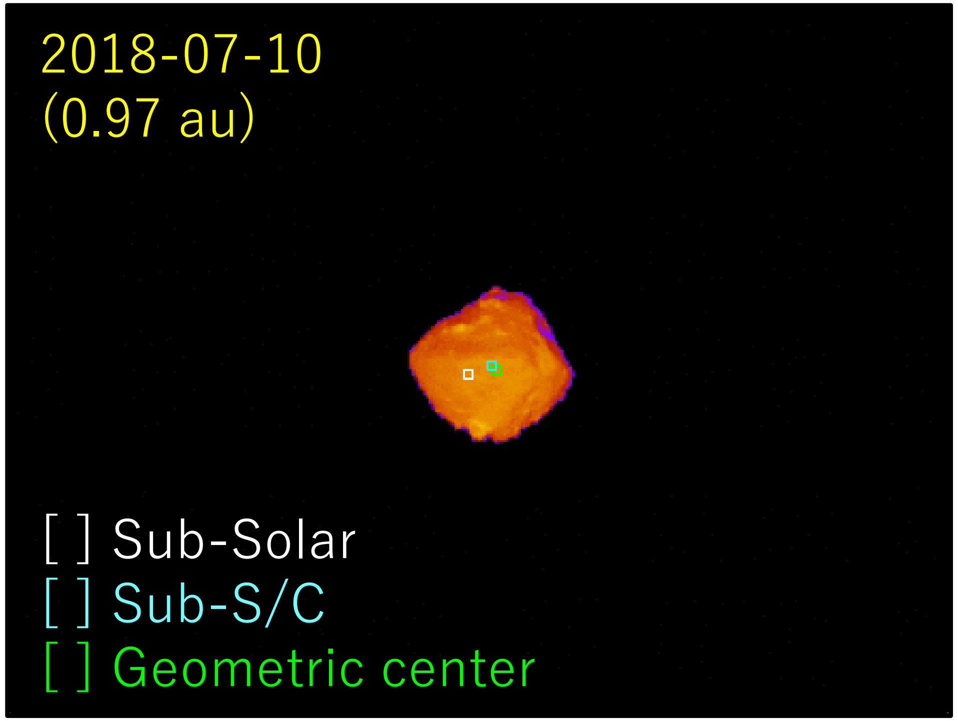
Fig. 1 Thermal images of Ryugu taken at 5 km altitude during the Mid-Altitude Observation Campaign.
a–d, Thermal images were taken on 1 August 2018 at the solar distance of 1.06 AU and the Sun–Probe–Earth angle of 19.0° : **a**, for the longitude (Lon) of 0° ; **b**, for the longitude of 90° ; **c**, for the longitude of 180° ; and **d**, for the longitude of 270° . Relatively higher temperatures in the southern hemisphere of the asteroid were due to the summer season. Geologic features are clearly identified such as Otohime Saxum (the largest boulder near the south pole, 160 m width) (**a**), Catafo Saxum (**b**), Cendrillon crater (**c**), Momotaro crater (**d**), Kibidango crater (**e**), Urashima crater (the largest crater, 270 m diameter) (**f**), Ejima Saxum (**g**), Kintaro crater (**h**), Tokoyo Fossa (**i**), Brabo crater (**j**), Kolobok crater (**k**) and Ryujin Dorsum (the equatorial ridge) (**l**)

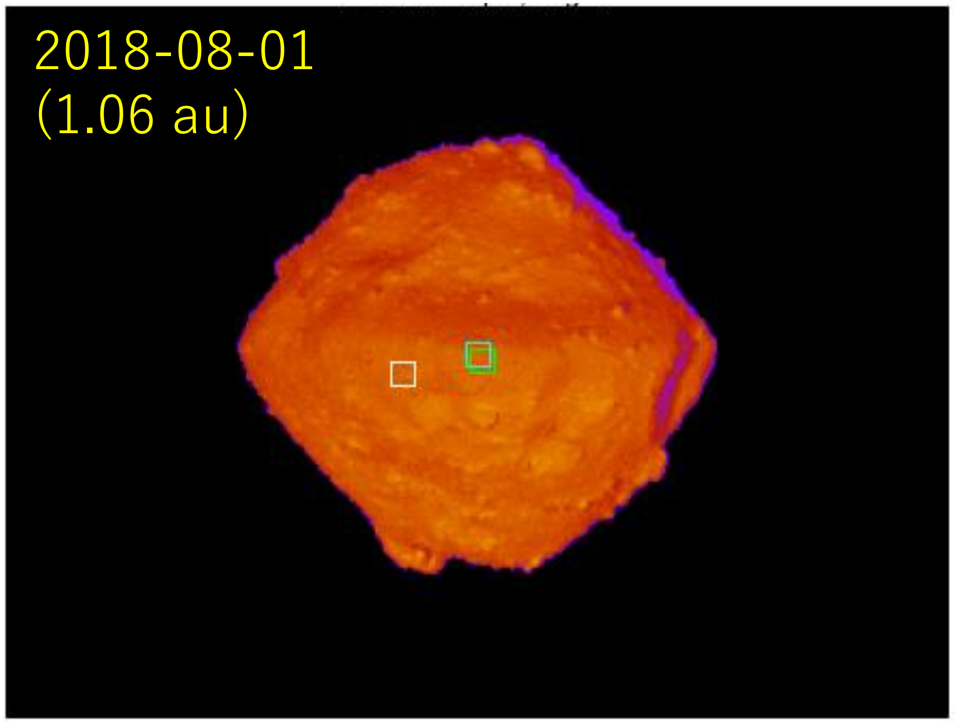
Example: Global thermal Images

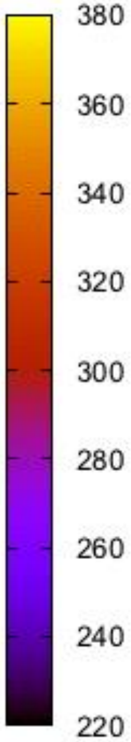
[Okada+, Nature 2020, Supplementary Information]

Box-A: 20km (~18m/pixel)

Mid-Alt: 5km (~4.5m/pixel)





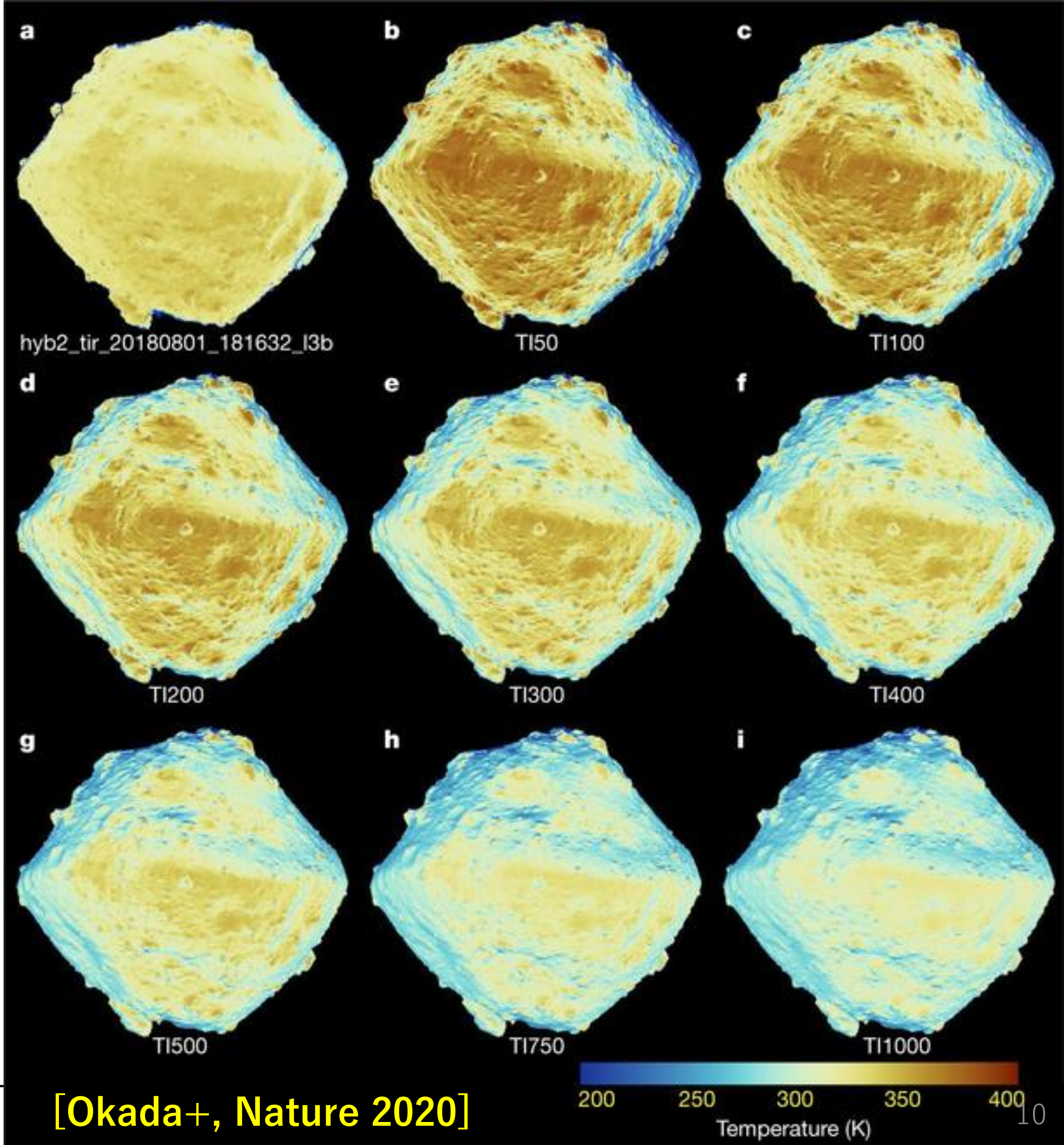


- TIR acquired >10k thermal images during the proximity phase
- **Box-A**: The first disc-resolved one-rotation global thermal images of an asteroid in history
- **Mid-Alt**: High-T boulders similar to surroundings → **No large dense boulders**

Fig.2 Global Thermal Inertia: Highly Porous!?

- Observed diurnal T-profiles are "Flat" compared to calculated ones with uniform TIs.
  - Highly rough surface
- Same T between boulders and the surroundings
  - Highly porous materials: TI = 300 ± 100 tiu, (Cf. typical C-chondrites: TI = 600-1000 tiu)
  - A single boulder, by MARA on MASCOT: TI = 282 $^{+93}/_{-35}$ tiu [Grott+, 2019]
  - Ground obs: TI = 150-300 tiu, [Mueller+, 2017]

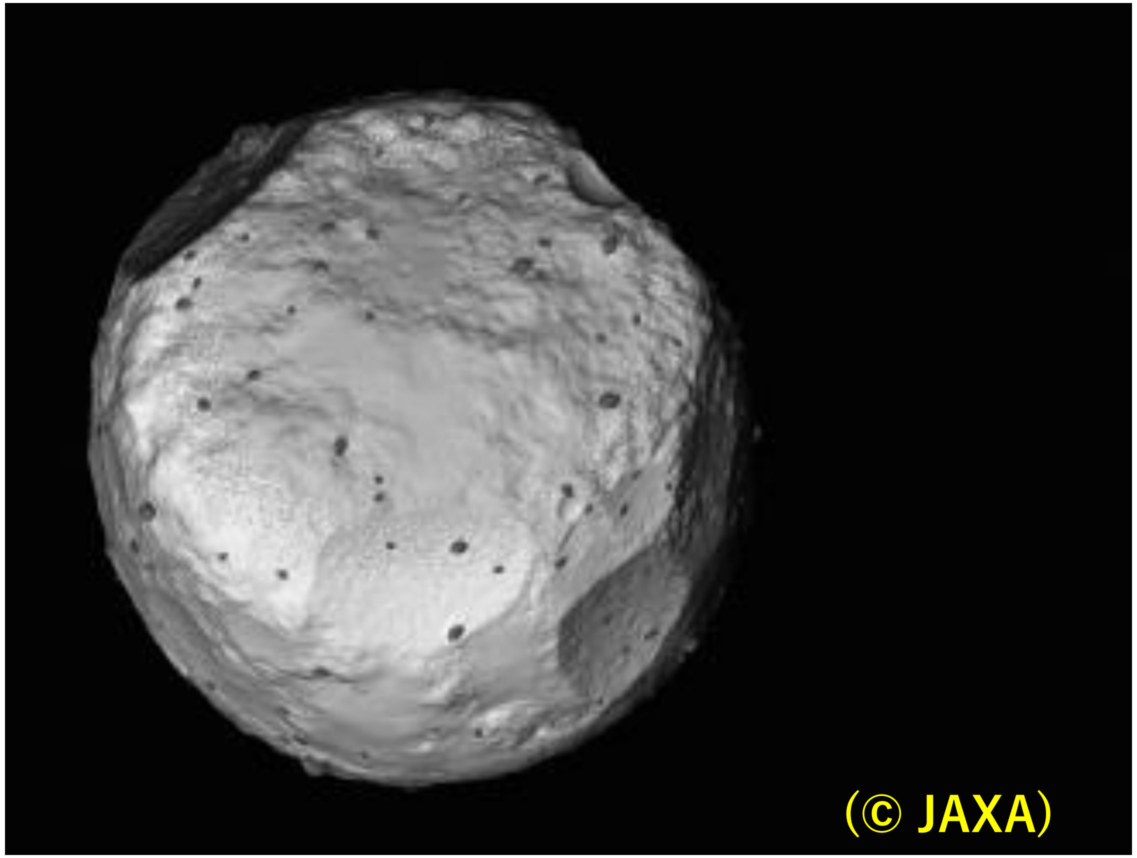
Fig. 2 Comparison of a temperature plot on the three-dimensional shape model with calculated images for thermal inertia of 50–1,000 tiu.
a, A temperature plot in kelvin on the asteroid Ryugu shape model (SHAPE_SFM_200k_v20180804), using the thermal image taken by TIR at 18:16:32 UTC on 1 August 2018 during the Mid-Altitude Observation Campaign.
b–i, Calculated thermal images that we compared with observations. **b**, Assuming a uniform thermal inertia of 50 tiu; **c**, of 100 tiu; **d**, of 200 tiu; **e**, of 300 tiu; **f**, of 400 tiu; **g**, of 500 tiu; **h**, of 750 tiu; and **i**, of 1,000 tiu. A thermal inertia of 300 ± 100 tiu matches the observation best.



[Okada+, Nature 2020]

Example: Boulders have "Unexpectedly Low" Thermal Inertia, indicating "highly porous" rocks

Ryugoid (Reference Asteroid)@Mid-Alt
(Exercise before arrival)
TI (assumed): Boulder: 1600tiu, Regolith: 300tiu



Ryugu (Observations) @Mid-Alt
(Observations at LT= 120° longitude)
TI (derived): Boulder & surroundings: ~300tiu

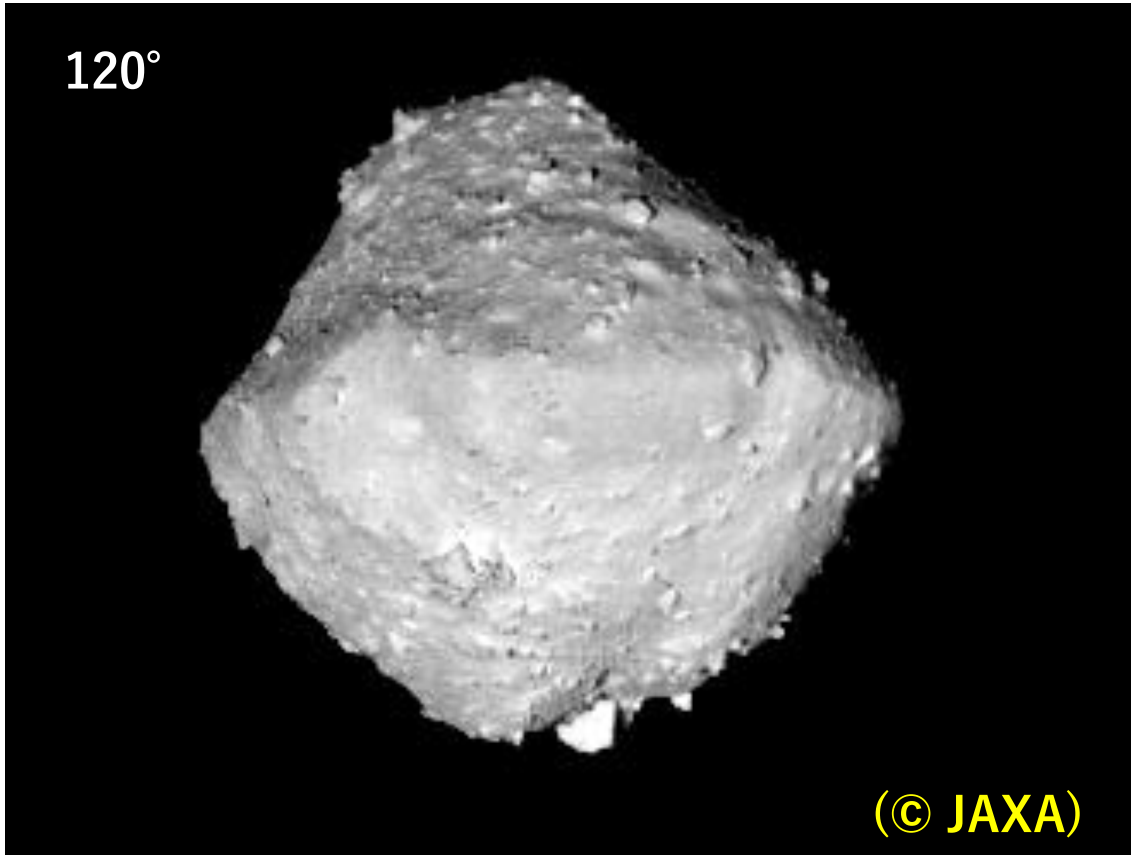


Fig.3 Max Temp and "Flat" Diurnal T-Profiles

- Diurnal T-profiles between boulders and the surroundings, compared with calculations
  - Highly porous materials with high very rough surface (less dependent on latitude).
  - Surroundings are dominated by fragments of highly porous materials > 10 cm (> thermal skin depth)

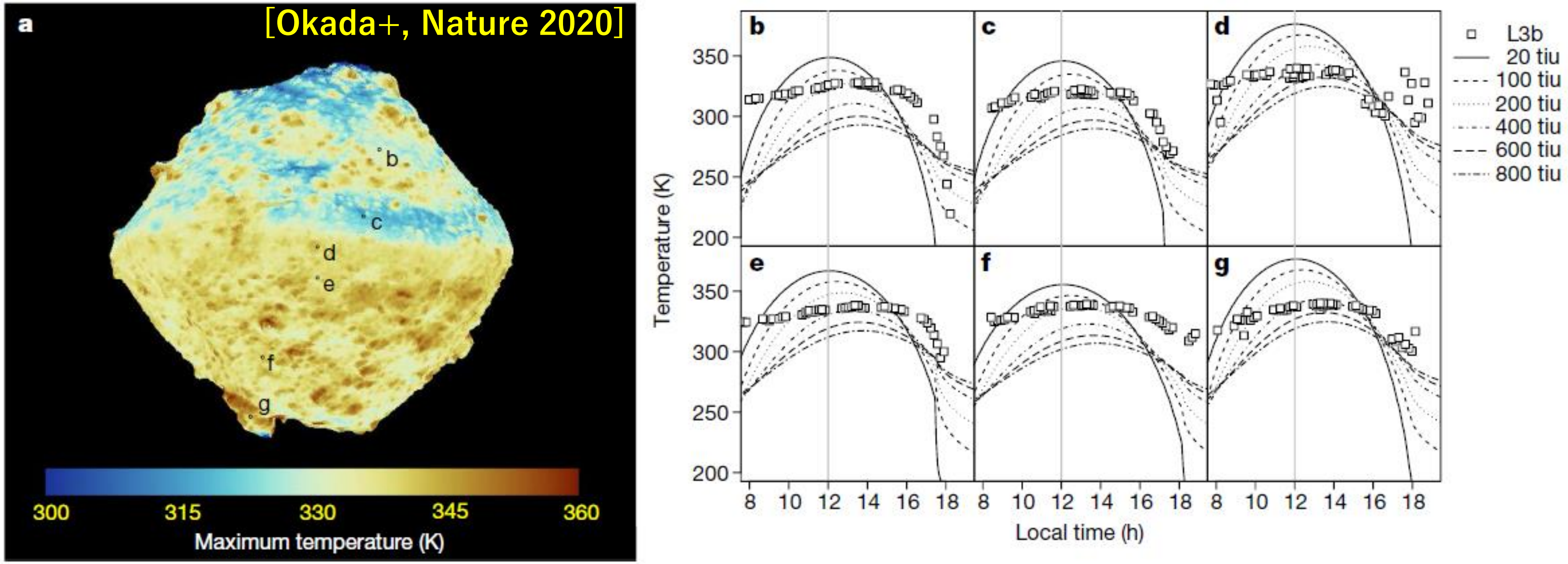


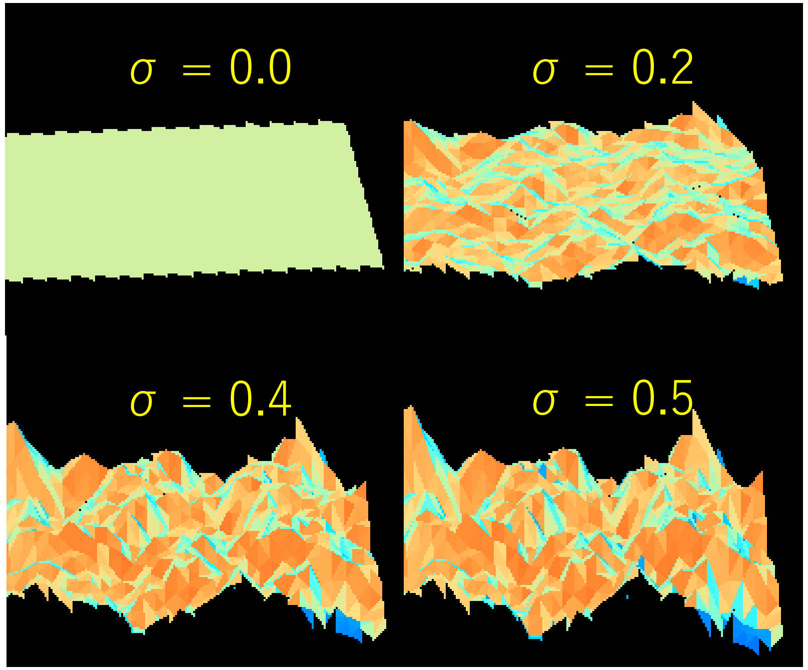
Fig. 3 Maximum temperature distribution during one rotation and the diurnal temperature profiles on Ryugu. a, Distribution of maximum temperature in kelvin during one rotation on 1 August 2018 plotted on the Ryugu shape model (SHAPE_SFM_200k_v20180804). **b–g**, Diurnal temperature profiles by TIR observation (squares) and by thermal calculation (lines or dotted lines) with uniform thermal inertias from 20 tiu to 800 tiu for each site labelled 'b' to 'g' in panel **a**, respectively. L3b is the level-3b product, which is brightness temperature plotted on the asteroid shape model. The polygon IDs, the positions in longitude and latitude, and site information for sites 'b' to 'g' are shown in Extended Data Table 1.

Example: Surface Roughness

Ref. 8: Shimaki+ (2019, LPSC) with the roughness model from Senshu+ (2019, LPSC)
→ Updated version: Shimaki+ *submitted to Icarus*

■ Thermophysical model with Rough Surface

- **Roughness parameter: σ**
  - Vertical displacement of vertex
- **Parameter search:**
  - TI: 10 to 800 tiu
  - σ: 0.0 to 0.5
  - Lat: -88° to 88°



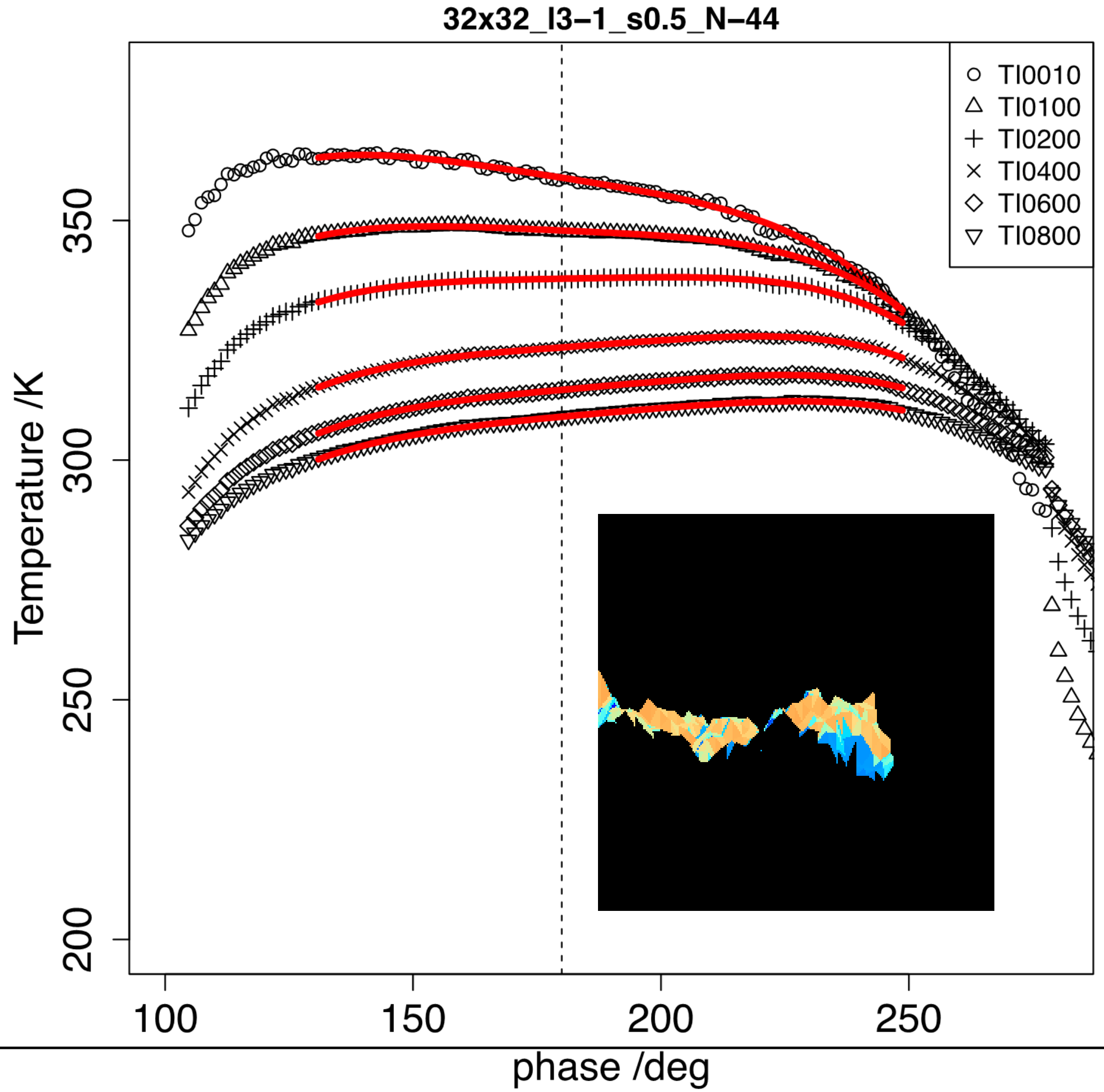


Fig.4 Close-up Thermal Images: “Cold Spots”

- **Typical surfaces proven to be covered with highly porous boulders & rocks (TI: 200-300 tiu) of the size > ~10 cm**
- **Discovery of colder boulders by 20 K as “Cold Spots”, corresponding to the dense rocks like C-chondrites (TI: 600-1000 tiu)**

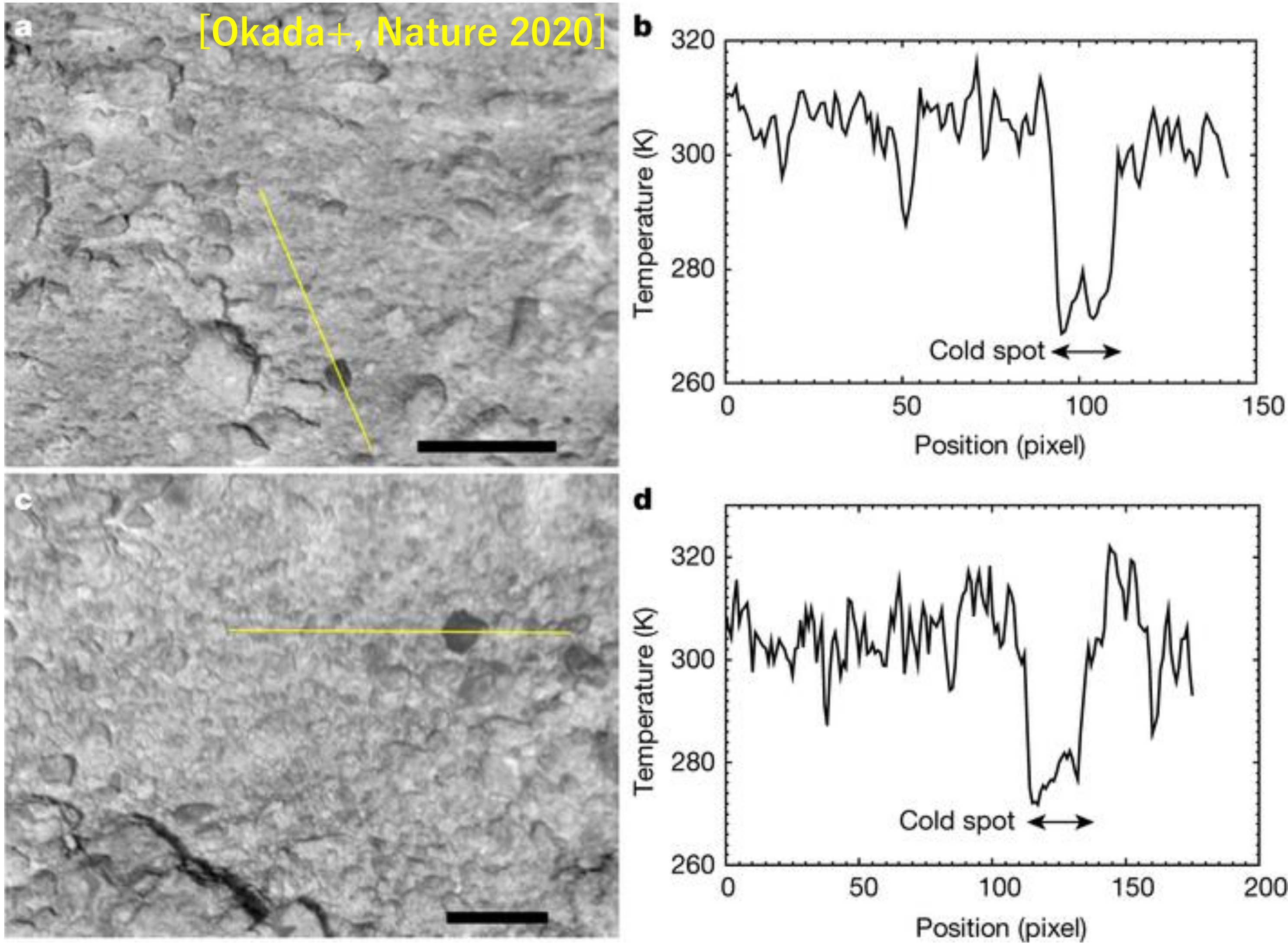
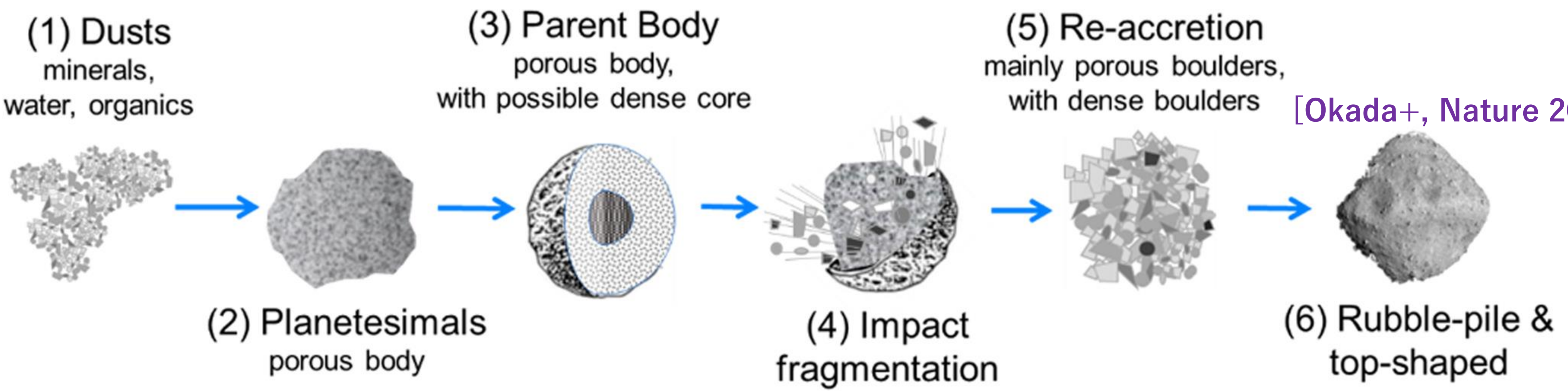


Fig. 4 Cold spots discovered in the close-up thermal images. **a**, A close-up thermal image taken during the TD1-R1-A campaign on 15 October 2018, at the solar distance of 1.28 AU and the Sun–Probe–Earth angle of 10.6° , at 13:34:44 UTC from an altitude of 78.8 m. **b**, The temperature profile along the yellow line in panel **a**, showing the ‘cold spot’ boulder. **c**, A close-up thermal image at 13:44:20 UTC at an altitude of 21.9 m. **d**, The temperature profile along the yellow line in panel **c**, showing the ‘cold spot’. The surface is covered with boulders, and most of them have similar temperatures. The ‘cold spot’ boulders are colder by more than 20 K, indicating dense and consolidated boulders with higher thermal inertia. Scale bars: 5 m in panel **a**, 1 m in panel **c**.

Extended Data Fig. 4: A Formation Scenario of Ryugu – A Porous Planetesimal Hypothesis

[Okada+, Nature 2020]



Extended Data Fig. 4. A formation scenario of Ryugu from a porous parent body. (1) Formation began with fluffy dust in the solar nebula. (2) Porous planetesimals were formed by accretion of dust or pebbles. (3) The parent body of Ryugu might have remained porous owing to a low degree of consolidation. A clear boundary of the inner core is illustrated but a gradual increase of consolidation by depth might be expected. (4) Impact fragmentation of the parent body occurred. Some large fragments are the boulders on Ryugu. (5) Part of fragments re-accreted to form Ryugu, with porous boulders and sediments on the surface, and some dense boulders originating from the inner core. (6) Re-shaping caused by a change in rotation rate to form a double-top-shape.

Summary

- Thermography of Ryugu (C-type asteroid) by TIR:
  - The first global one-rotation thermal images of an asteroid in history!
  - The first high-resolution and close-up thermal images of asteroid surfaces as well!
- Discoveries! (Surprises!!)
  - Similar temperatures between boulders and their surroundings, indicating same materials
  - Highly porous materials indicated by their very low thermal inertia (TI) of ~300 J m^{-2} $s^{-0.5}$ K^{-1} (tiu), Cf. typical TI of C-chondrites: 600-1000 tiu.
  - Surroundings are NOT covered with regolith but with >10 cm-sized porous fragments
  - Flat diurnal temperature profiles suggesting a strong surface roughness effect.
  - Discovery of cold boulders “Cold Spots” with TI > 600 tiu, typical dense C-chondrites.
- New Formation scenario of Ryugu:
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  - Materials have never experienced substantial consolidation or compaction.
  - Dense boulders from the more consolidated core of the parent body or an exogenic origin.
- This low-porosity asteroid may link cosmic fluffy dust to dense celestial bodies.

Appendix

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Extended Data Table 1

Ryugu site information for diurnal temperature profiles

[Okada+, Nature 2020]

Site	Polygon ID	Longitude	Latitude	Remarks
b	157464	27.8 °E	32.5 °N	Smooth region in northern mid latitude
c	152944	13.9 °E	3.9 °N	Smooth region in northern low latitude
d	147342	0.2 °E	5.5 °S	Catafo Saxum (boulder, PM landmark)
e	147896	2.7 °E	18.3 °S	Smooth region in southern mid latitude
f	194355	329.1 °E	47.0 °S	Smooth region in southern low latitude
g	183108	290.4 °E	68.8 °S	Otohime Saxum (boulder)

PM: Prime meridian

Extended Data Table 2 TIR major operations at Ryugu before mid-October 2018 used in this study

[Okada+, Nature 2020]

	Date	Solar distance [au]	SPE angle [deg]	Lowest Altitude	Maximum Resolution [/pixel]	Contents of TIR Observations
1	2018/06/06	0.964	16.7	2000 km	Point source	Light curve observations & search for moons
2	2018/06/18	0.971	17.7	200 km	180 m	Light curve observations & search for moons
3	2018/06/30	0.986	18.5	20 km	18 m	Light curve observations & search for moons // First set of HR global thermal images of an asteroid
4	2018/07/10	1.004	19.0	20 km	18 m	Global mapping for 1 rotation : Box-A
5	2018/07/20	1.027	19.2	6.5 km	6 m	Global mapping for 1 rotation : Box-C
6	2018/08/01	1.056	19.0	5 km	4.5 m	Global mapping for 1 rotation : Mid-Altitude
7	2018/08/06-07	1.073	18.7	< 1 km	0.9 m	HR images : Gravity Measurement
8	2018/08/25	1.127	17.5	22 km	20 m	Global mapping for 1 rotation : Box-B (South pole)
9	2018/08/31	1.145	16.9	22 km	20 m	Global mapping for 1 rotation : Box-B (Dusk side)
10	2018/09/20-21	1.209	14.4	50 m	4.5 cm	Close-up images: MINERVA-II release
11	2018/10/03-04	1.244	12.6	50 m 2~3 km	4.5 cm 1.8 m	Close-up images: MASCOT release HR images : MASCOT hovering at 3 km
12	2018/10/14-15	1.273	10.8	10 m	0.9 cm	Close-up images: TD1-R1-A

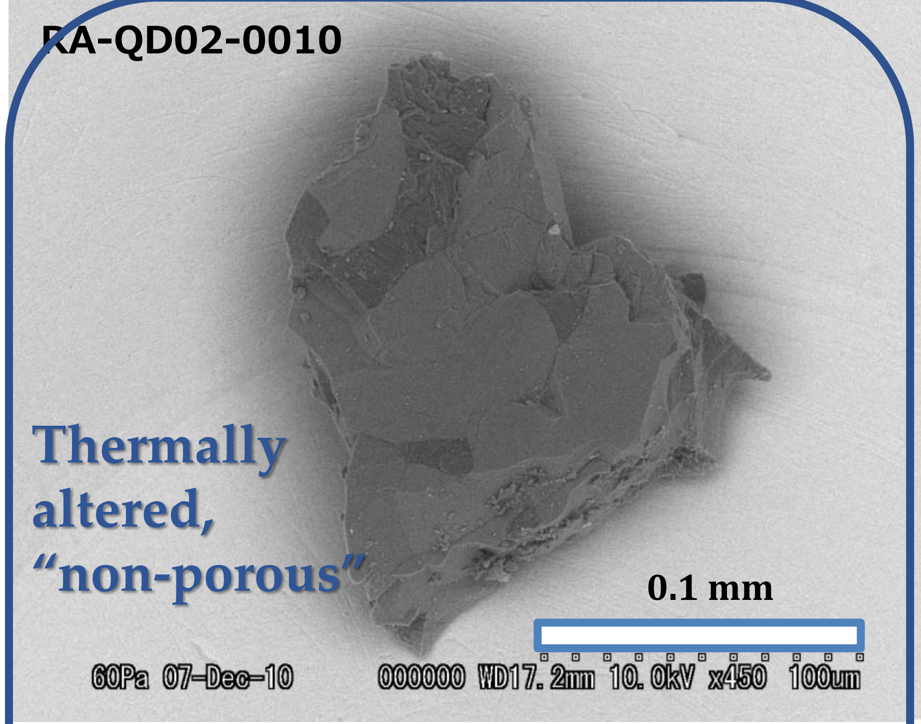
SPE, Sun-Probe-Earth HR, high-resolution

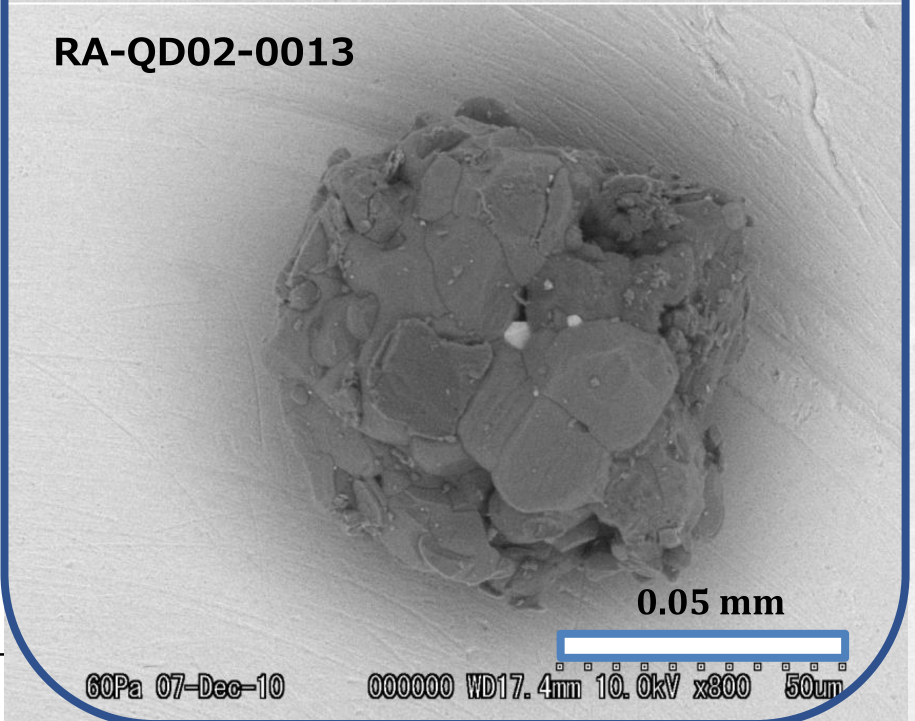
Example: Itokawa sample by Hayabusa

◆ Asteroid 25143 Itokawa (S-type) consists of mainly LL5-6 materials (thermally altered and non-porous, Left two), but some minor portions of LL3-4 with fluffy aggregates (primitive, fine-grained, and porous Right two)

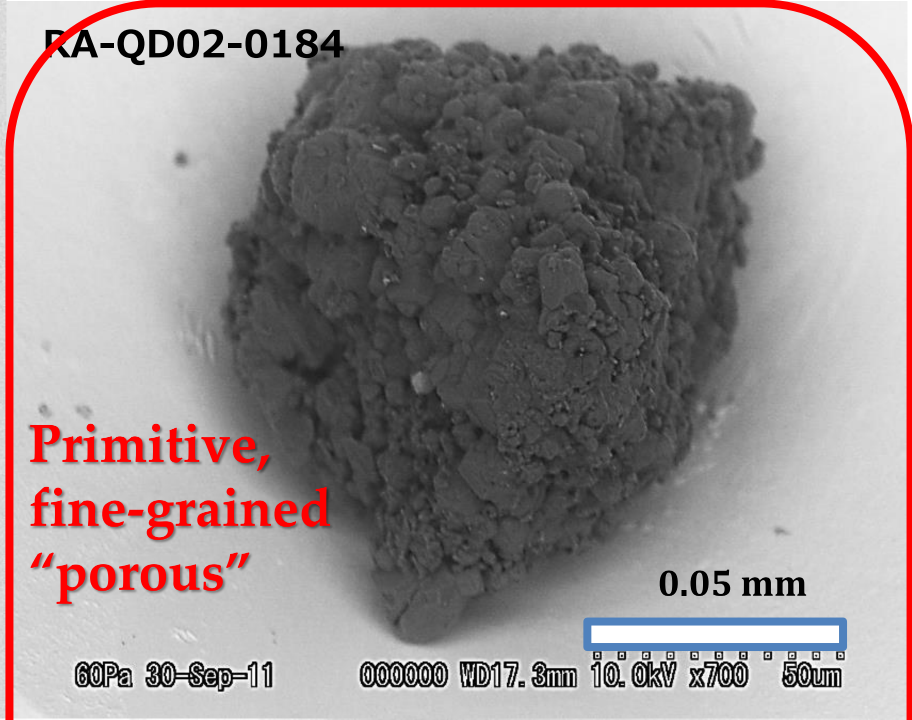
[Images from JAXA/ASRG]
https://curation.isas.jaxa.jp/ao/docs/sample_top.html

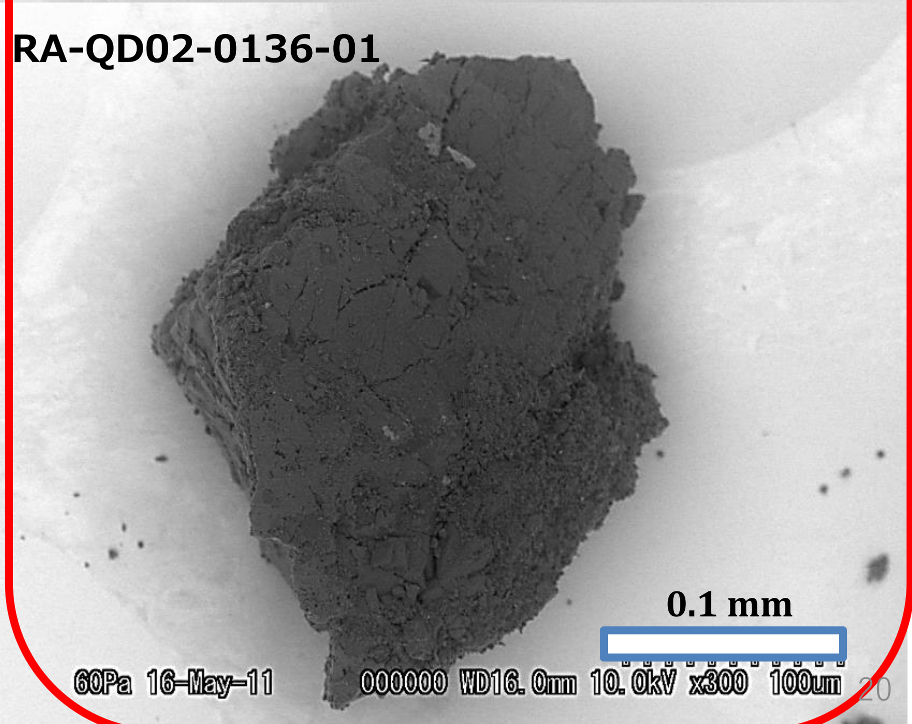
Thermally altered, "non-porous"





Primitive, fine-grained "porous"





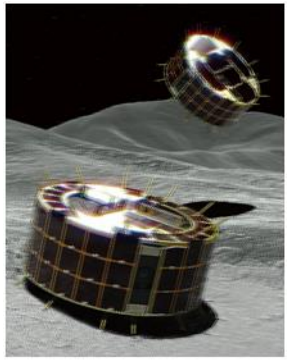
Outline of Hayabusa2 Mission Flow

Launch
December3, 2014

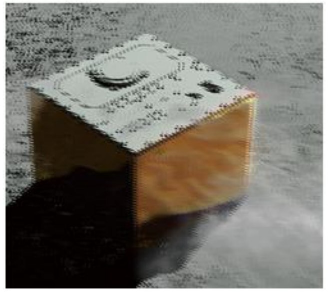
Earth swing-by
December 3, 2015

Asteroid arrival
June 27, 2018

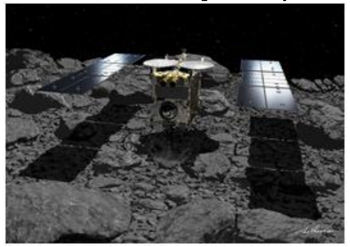
MINERVA-II-1
September 21, 2018



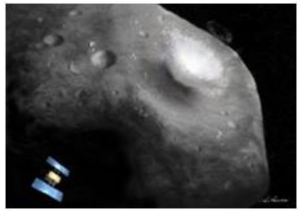
MASCOT
October 3, 2018



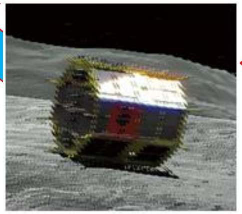
1st Touchdown
February 22, 2019



Impactor
April 5, 2019



2nd Touchdown
July 11, 2019



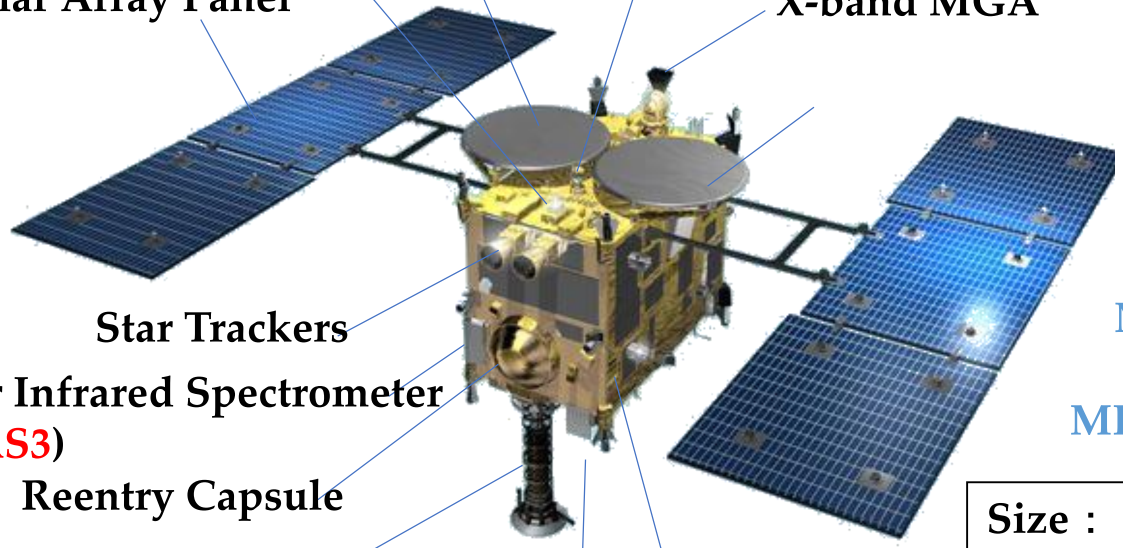
MINERVA-II-2 & TM

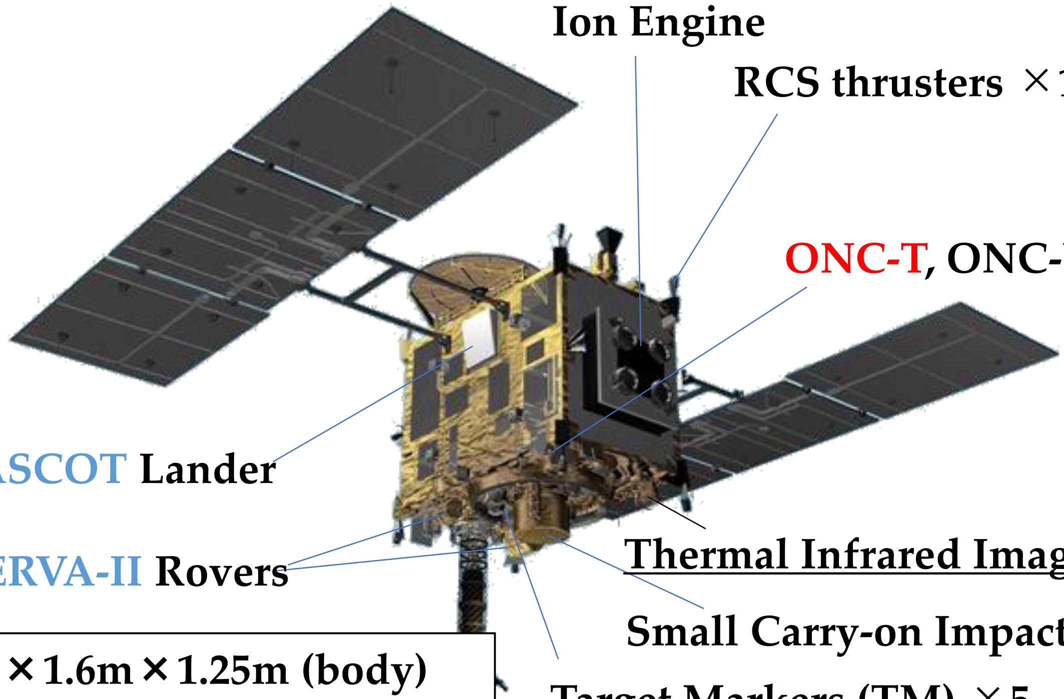
Asteroid departure
Nov 13, 2019

Earth return
End of 2020

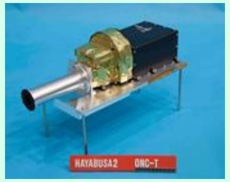
(image credit: illustrations including spacecraft by Akihiro Ikeshita, others by JAXA)

Hayabusa2 Spacecraft



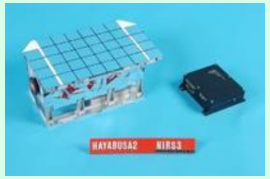


Size： 1m×1.6m×1.25m (body)
Mass： 609kg (Wet)



ONC-T

LIDAR



NIRS3

TIR

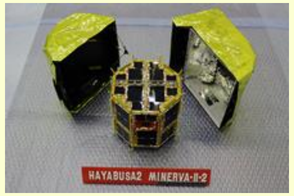
Science Instruments

MASCOT

by DLR and CNES

MINERVA-II-1

MINERVA-II-2



II-1 : by JAXA MINERVA-II Team
II-2 : by Tohoku Univ. & MINERVA-II consortium

Small Lander and Rovers

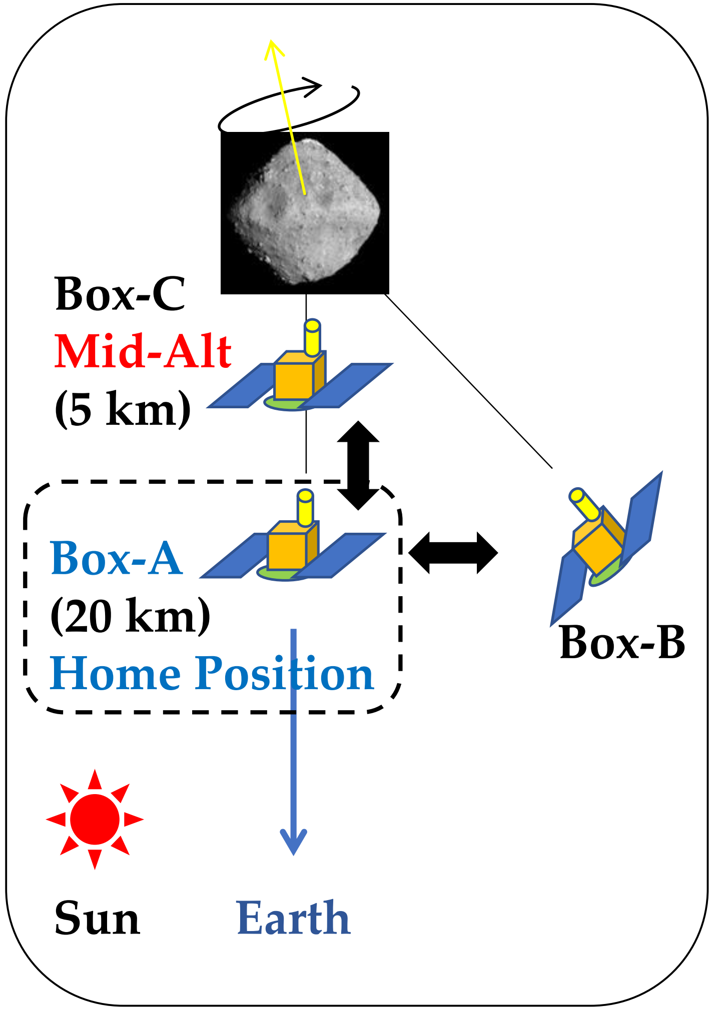
(image credit : JAXA)

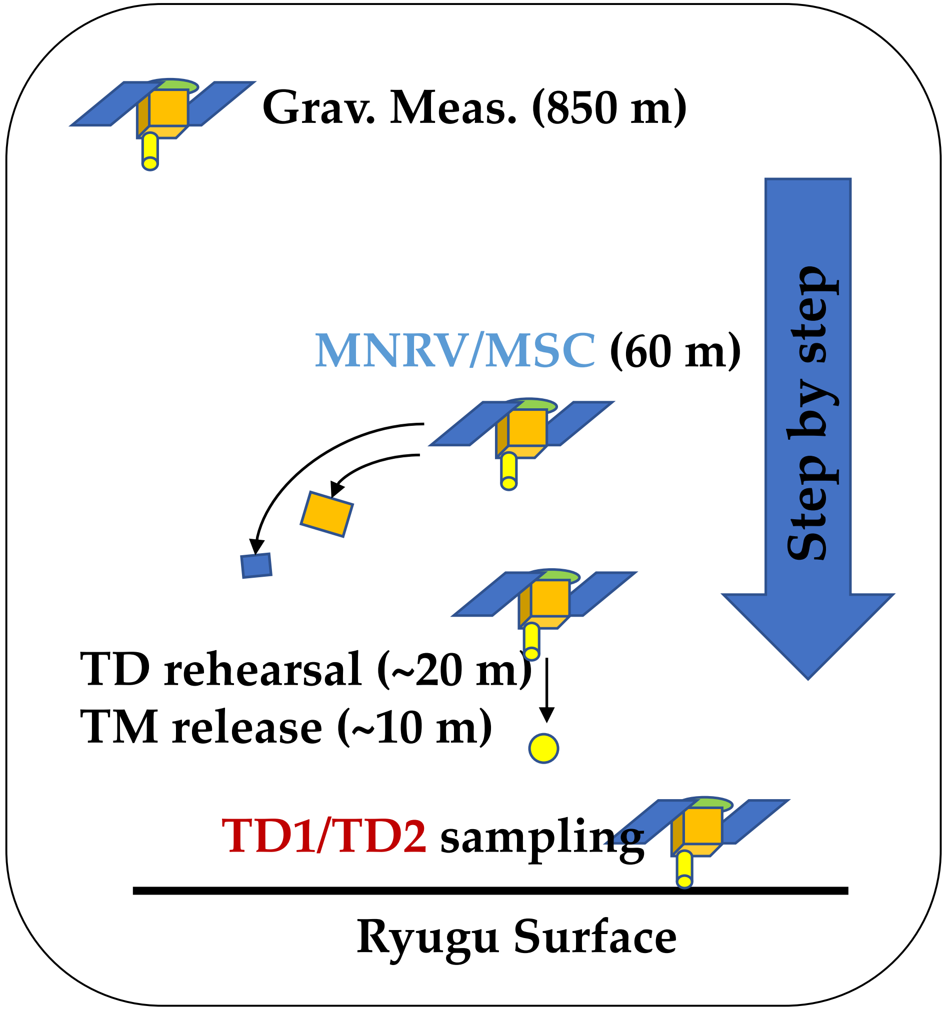
Hayabusa2 Operations

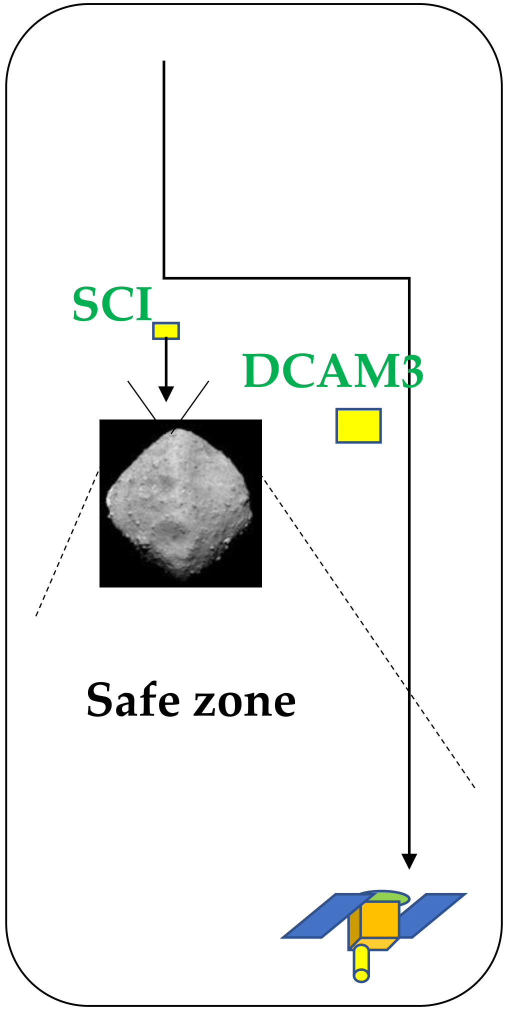
Hovering Ope.:
One-rotation Obs.

Descent Ope.:
Rehearsals for Touchdown

SCI Ope.:
Impact exp.





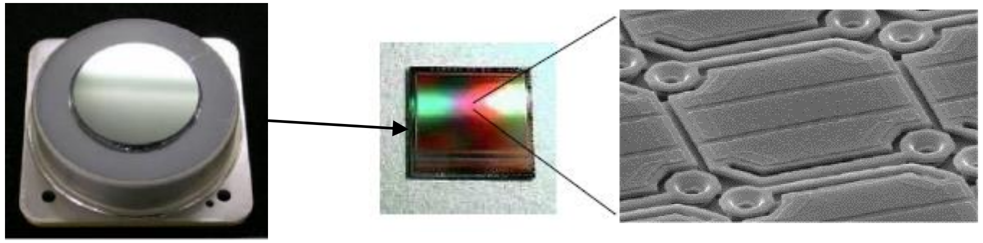


(image credit : JAXA)

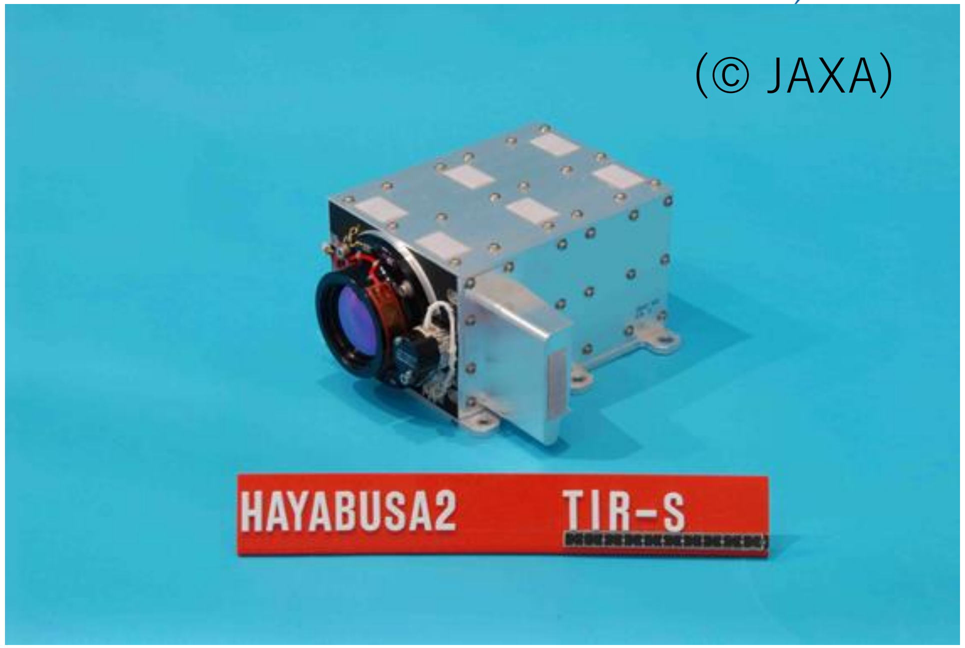
TIR (Thermal Infrared Imager)

■ Uncooled Micro-Bolometer Array

→ Light-weighted thermal infrared imager



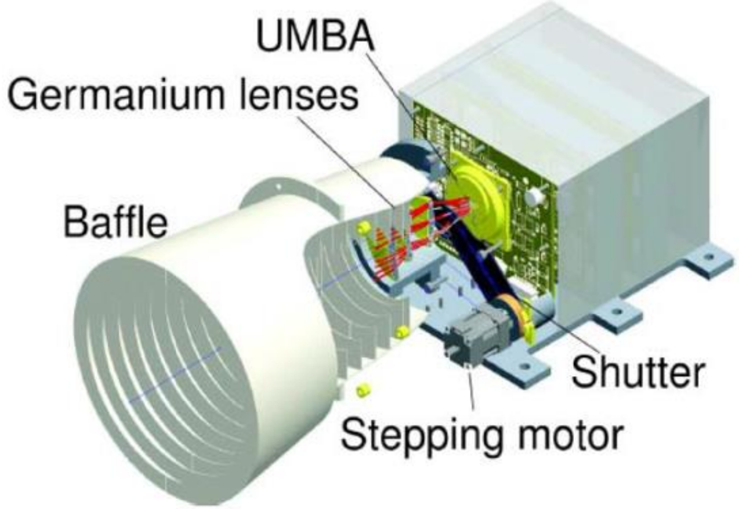
[Hihara+ 2014]



■ Specifications of TIR

→ Light-weighted thermal infrared imager

・Total Mass	: 3.28 kg
・Power Consumption	: <20W
・Detector	: 2D uncooled bolometer
・Observation wavelength	: 8–12 μm
・Observed temperatures	: −120 to +150 °C
・Relative accuracy(NETD)	: < 0.3 °C
・Dimensions	: 328 × 248 (effective)
・Field of View	: 16.7°×12.6°
・Spatial Resolution	: 18 m (20-km alt./HP)
	: 5 cm (50-m alt./Mid-Alt)
・No. of Summation	: 2^N (N=0,1,2,…,7)

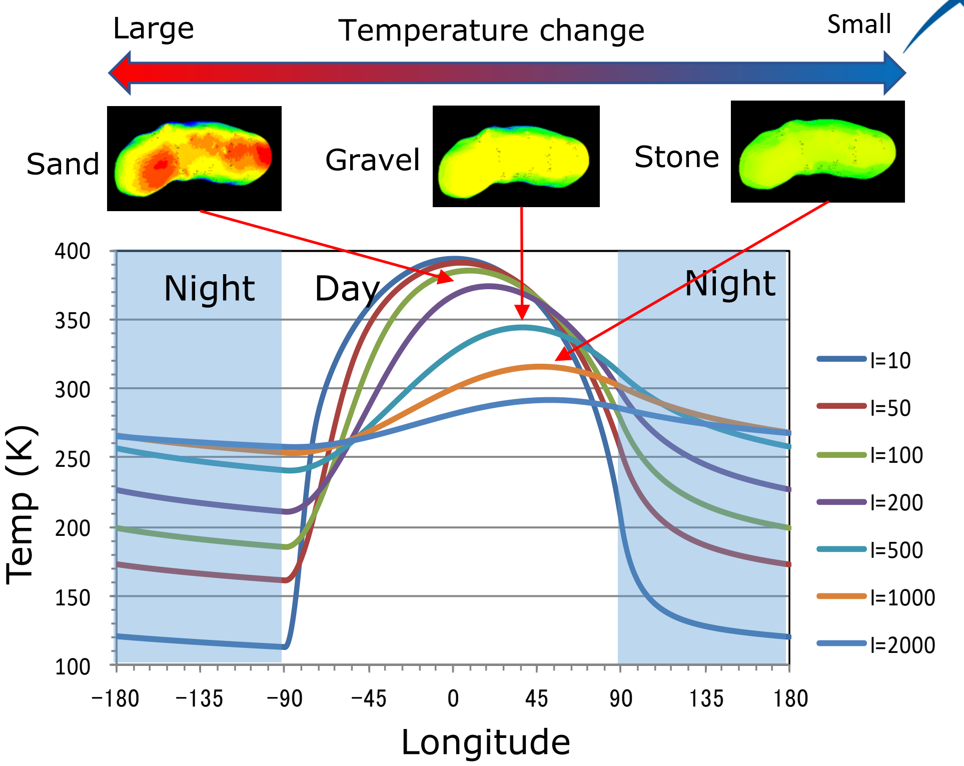


[Fukuhara+ 2011 EPS] ,for Akatsuki Venus Orbiter

TIR Principle of Observation

- **The first thermography in planetary missions, to study the physical state of asteroid surface.**
- **TIR observes the change of asteroid surface temperature over the day, rising in sunlight and decreasing at night.**
- **Diurnal temperature change is larger for fine soils or porous materials (low thermal inertia: TI), and smaller and delayed for dense rocks (high TI).**

[Okada+, 2014]

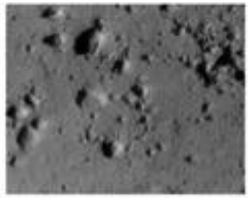
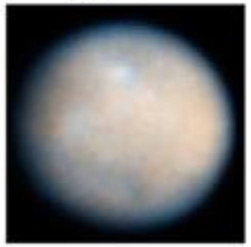


➢ Thermal Inertia (TI)

- Surface physical state (porosity, grain size)
- Thermal inertia (TI, J m^{-2} K^{-1} $s^{-0.5}$): Resistance to T change

$$\Gamma = \sqrt{\kappa \rho c_{\mathrm{p}}}$$

κ : Thermal conductivity
ρ : Density
c_{p} : Heat capacity

25143 Itokawa	433 Eros	The moon	1 Ceres
$\Gamma = 600$	$\Gamma = 150$	$\Gamma = 50$	$\Gamma = 10$
			
Coarse regolith and boulders	Finer and thicker regolith	Mature and fine regolith	Very fine regolith ??