



# Optical and low frequency radio observatory on the Moon

H. Noda<sup>1</sup> , H. Hanada<sup>1</sup> , T. Iwata<sup>2</sup> , N. Kawano<sup>1</sup> , S. Sasaki<sup>1</sup> , H. Araki<sup>1</sup> , and T. Imamura<sup>2</sup>

1 NAOJ, Japan 2 ISAS/JAXA, Japan



# outline

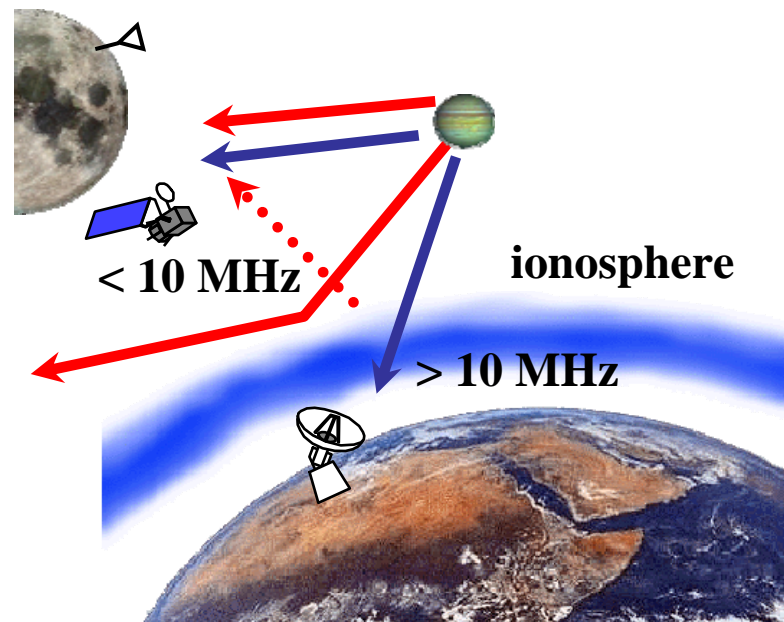
- Low Frequency radio astronomy ( LLFAST )  
-- lunar ionosphere measurement by SELENE
- In-situ Lunar Orientation Measurement (ILOM)
- summary

# 1 Low frequency radio telescope

# Observational Limits of the Very Low Frequency

Very low frequency (< 10 MHz) is the last frontiers for astronomy because;

- The terrestrial ionosphere prevents observing the radio waves below the ionospheric cutoff frequency on the ground.
- The interferences are caused by the artificial noises, solar burst, and terrestrial aurora emissions on orbits.



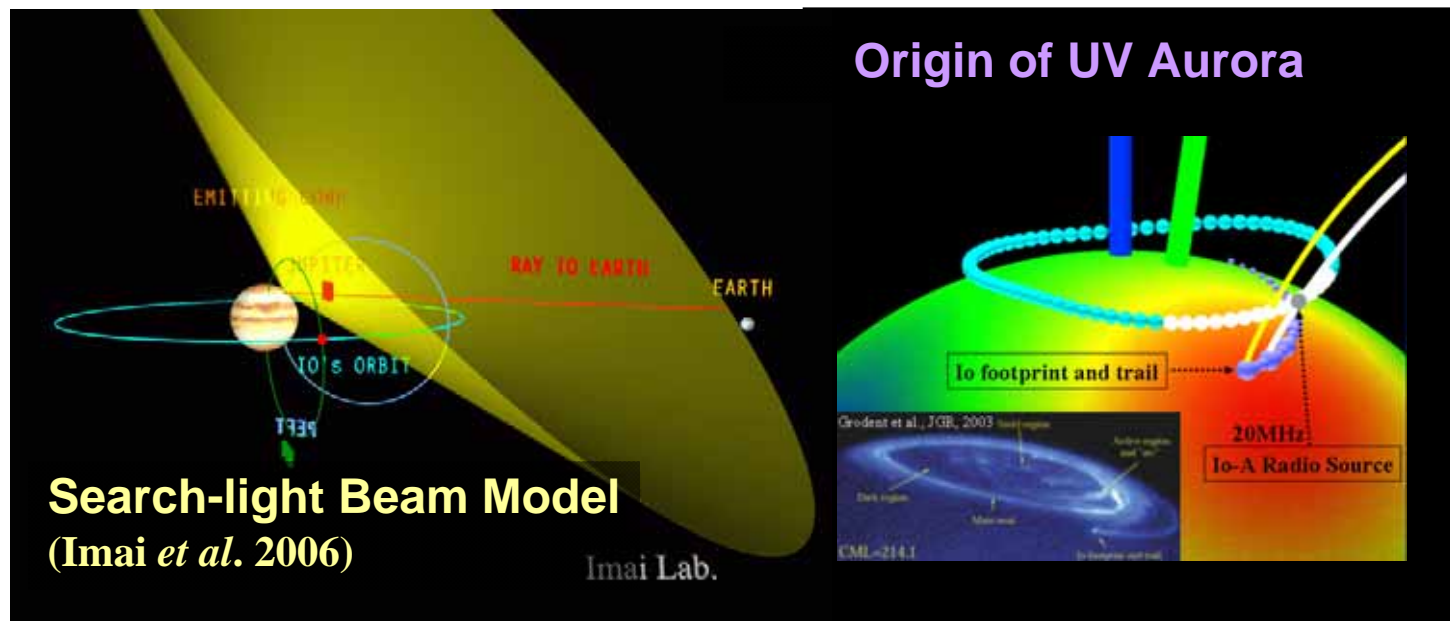
# Low Frequency Planetary Science

Our Solar System :

- Jupiter ; Mechanism of Io-DAM (Decameter wave)
- Saturn, Uranus, Neptune
- Sun ; Mechanism of Type III burst

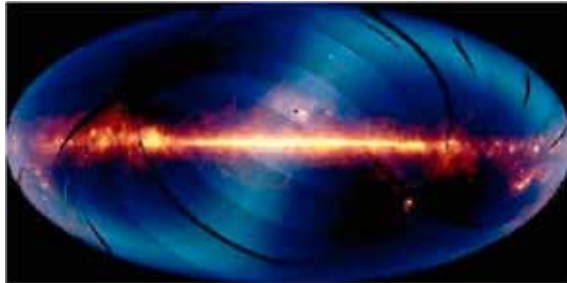
Extra Solar System :

- Jupiter-like Planet Survey



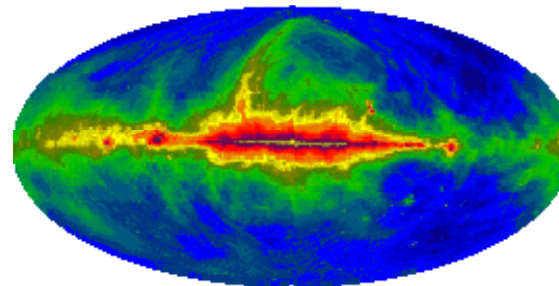
# Low frequency astronomy

←high frequency/ high energy



IRAS Survey (Beichman *et al.* 1988)

longer wavelength→



Bonn 408 MHz Survey

???

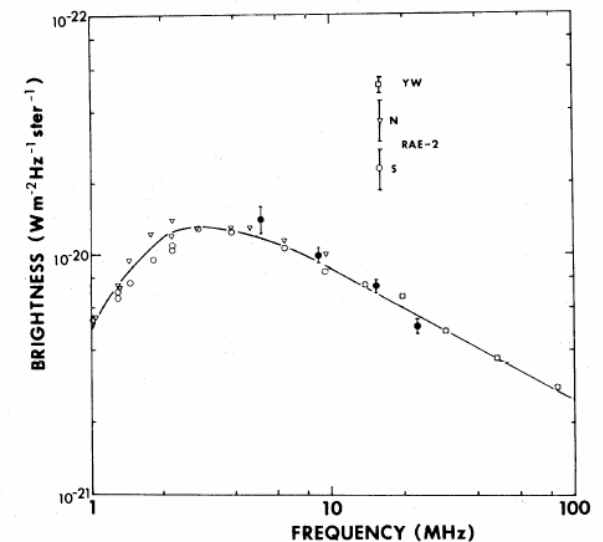
< 10 MHz

## physical processes

- Low temperature/density
- Absorption by cold electron
- Synchrotron self absorption
- free-free absorption

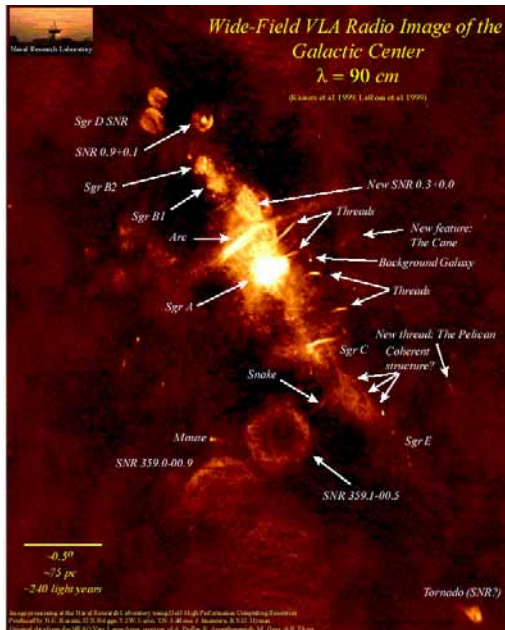
## targets

- SNR (super nova remnant)
- Spatial distribution of electron in our galaxy ...



Free-free absorption by low temperature/low density plasmas in the galactic plane ?  
T<sub>e</sub>=6000[K] Ne=0.1/cc ??

# Future astronomical targets



← SNR survey at 330MHz toward Galactic Center (La Rosa *et al.* 2000)

## targets

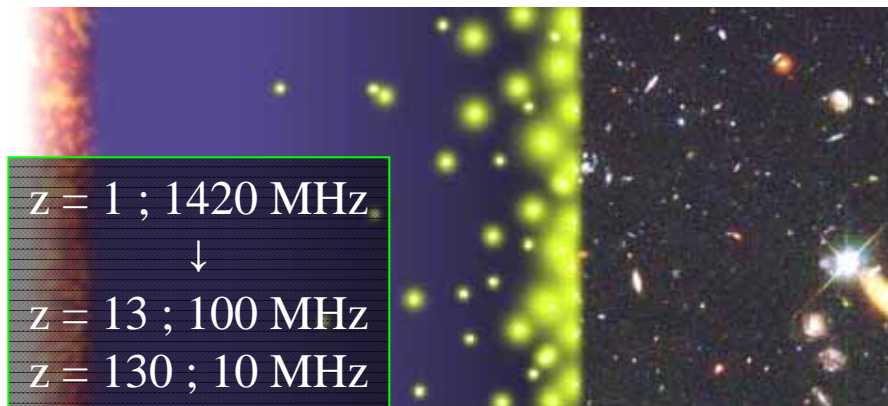
- Lower-energy SNR (super nova remnant)
- Spatial distribution of lower-energy materials in our galaxy, inter-galaxy
- Large scale distribution of cosmic web structures

$z \sim 1000$   
recombination



$z \sim 10$   
reionization

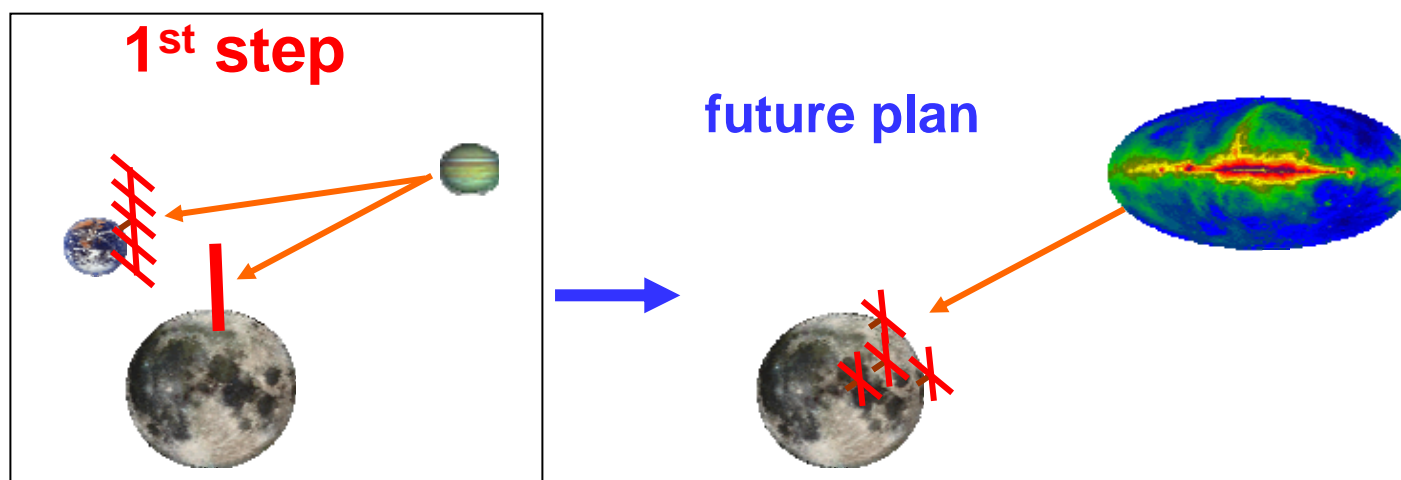
after Djorgovski *et al.*



↑ Big Bang

# 1<sup>st</sup> Step Lunar Low Frequency Observatory

	1 <sup>st</sup> step	future plan
configuration	Moon (1 element)-Earth interferometer	Interferometer on the Moon
site	pole or midlatitude	far side
frequency	20 - 25 MHz	0.1 – 20 MHz
targets	Jupiter	galactic and extra-galactic objects, etc.

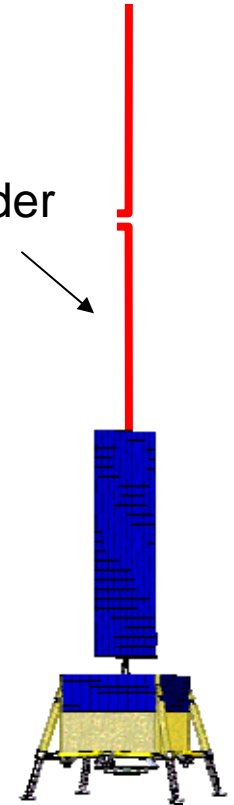


# System of 1<sup>st</sup> Step (TBD)

## 1) Lunar Observatory

component, mass	- 7m antenna; 2 kg (antenna + mechanism) - receiver system; 200 g (amplifier, sampler, frequency standard)
power	2 W (during observation)
frequency	20 - 25 MHz
data handling	sampling; 10 MHz, 8 bit, 1ch down-link; < 1.4 Mbps

Antenna on  
SELENE-2 Lander



## 2) Candidate Ground Observatory

- Agawa, Kouch NCT (picture ->)
- Iidate, Tohoku U.
- Kashima, NICT
- Fukui Univ. Tech.



# Research and Development (1)

## 1) Thermal Cycle Test (Fig. 1)

\* +80 ~ -200 °C

\* Amplifier, AD Converter, *etc.*

## 2) Selection of Frequency standard (Fig. 2)

\*  $10^{-9}$  small-scale low-power type

## 3) Evaluation of Stem antenna (Fig. 3)

\* LRS (Lunar Rader Sounder) on SELENE

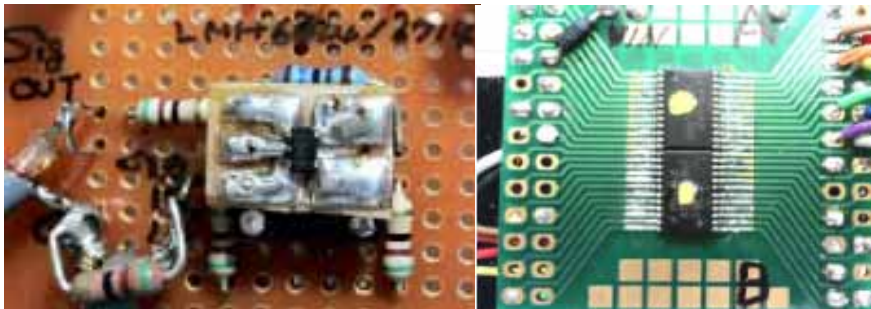


Fig. 1



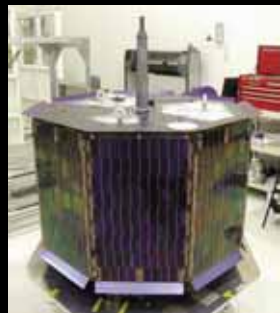
Fig. 2



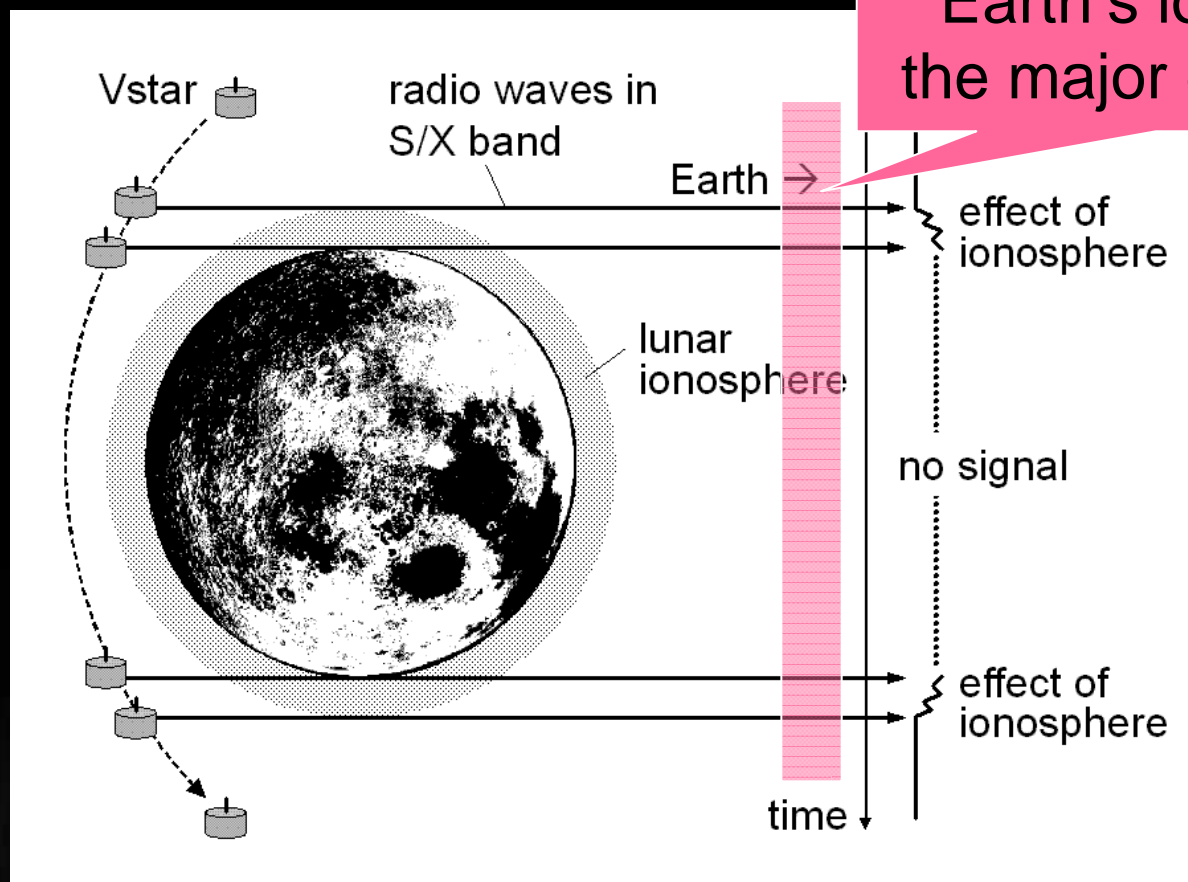
Fig. 3

# Research and Development(2) SELENE RS

- To clarify whether **lunar ionosphere** exists or not
- To study the origin of the ionosphere by comparing results under different conditions



Vstar subsatellite



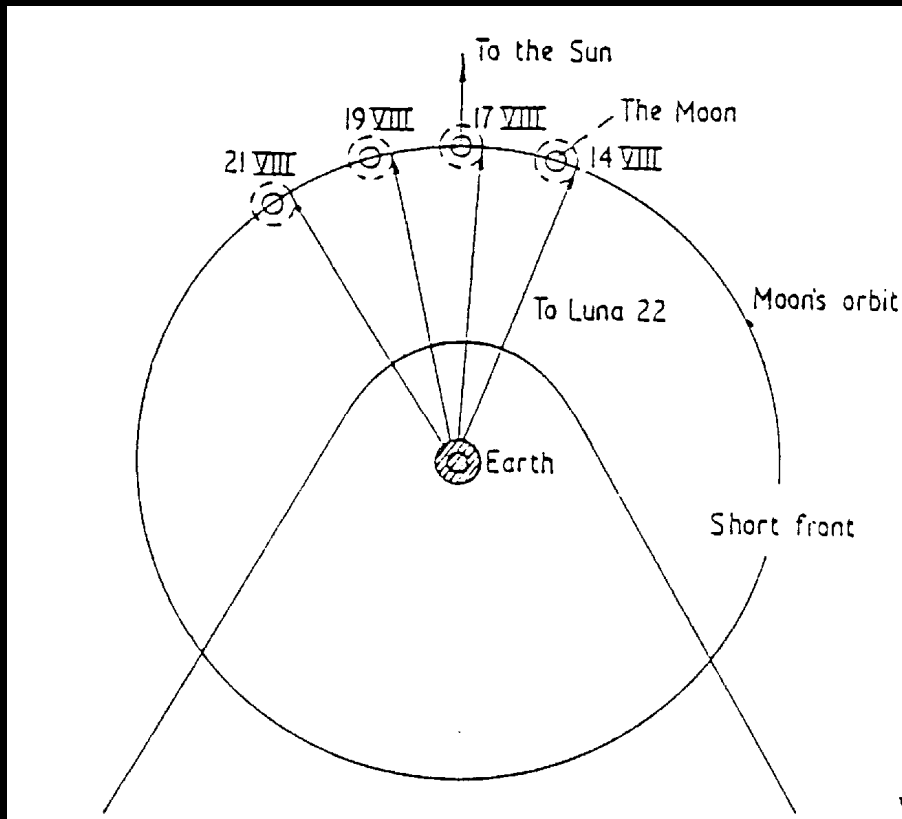
Earth's ionosphere:  
the major error source



Usuda Deep  
Space Center,  
Japan

(T. Imamura, AOGS 2008)

# Radio occultation observation of the lunar ionosphere by Soviet Luna 22 (Vyshlov, 1976)



Regions near the morning terminator were explored.

(T. Imamura)

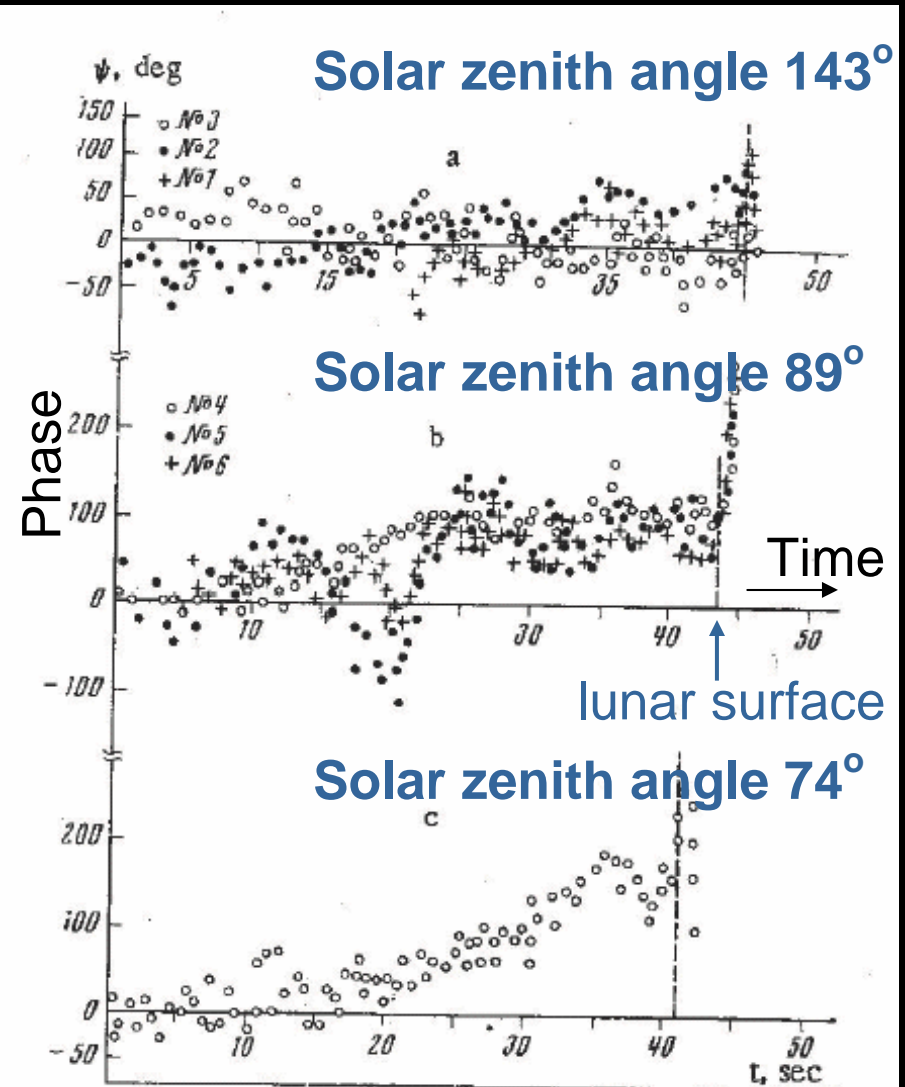
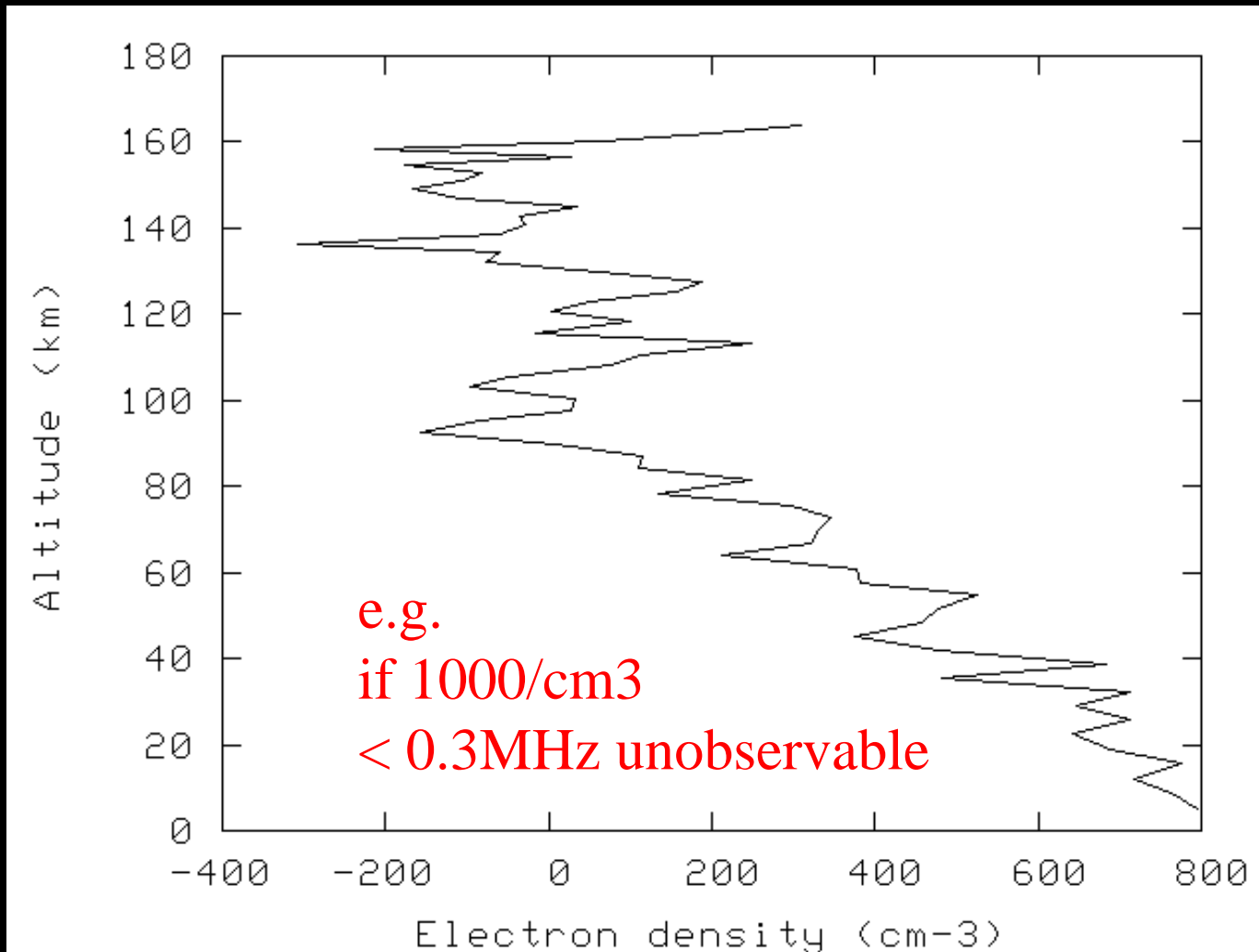


Fig. 1. Variation in reduced phase difference during radio transparency measurements of circumlunar space.

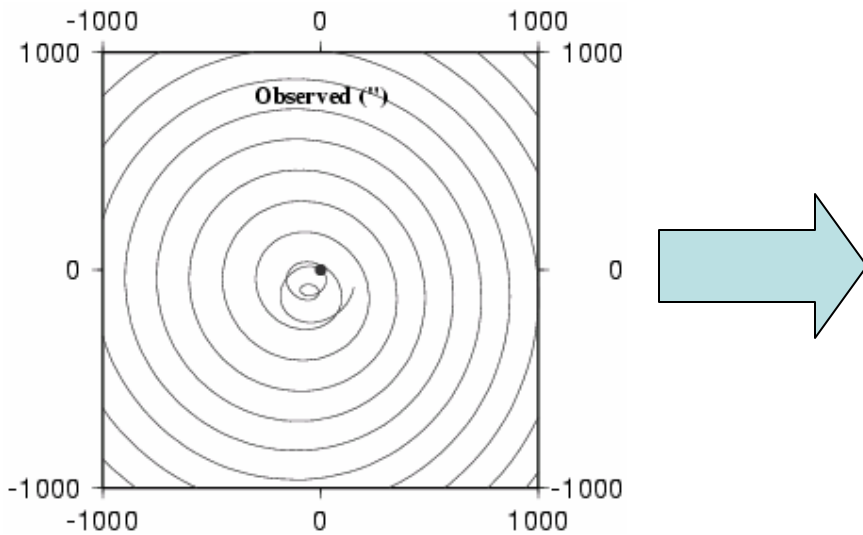
# An example of the electron density profile near the morning terminator





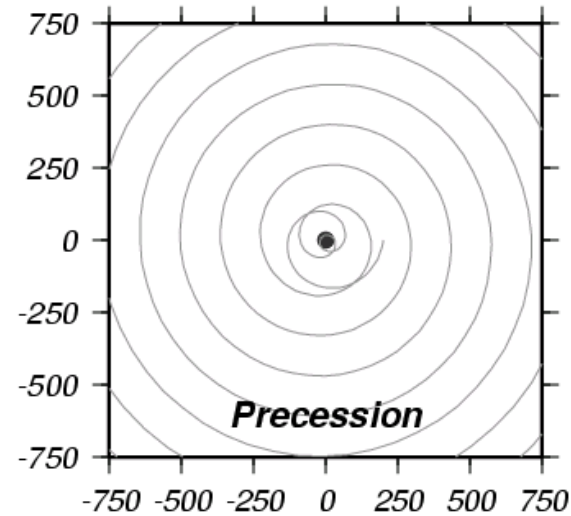
# Star trajectory and Effects of Librations

Trajectory of a star observed at the Lunar pole (June 2006– Sep.2007)

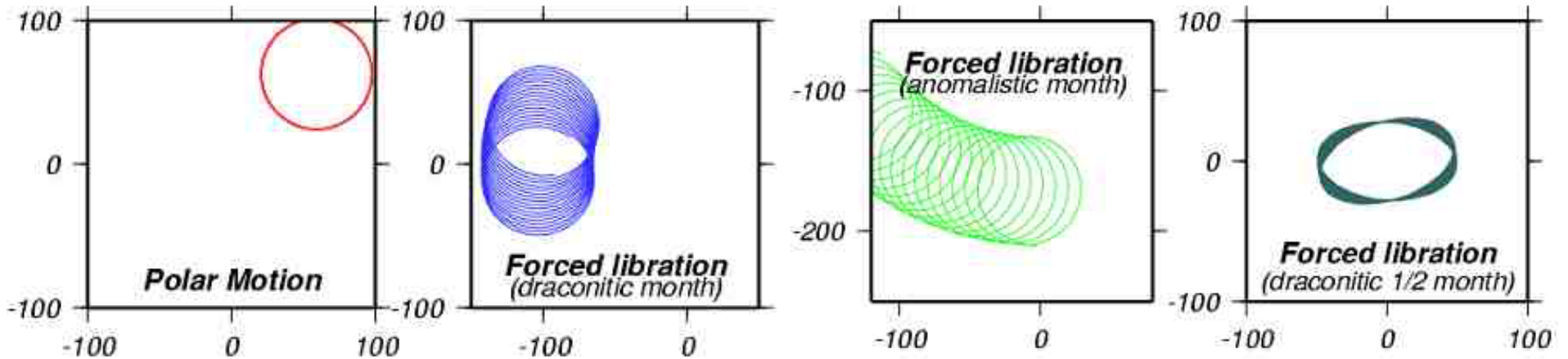


Decomposition of the trajectory

After Heki



Polar motion and Librations extracted from the trajectory



# ILOM (In-situ Lunar Orientation Measurement)

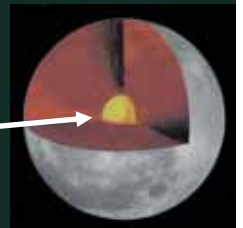
Observation of the lunar physical librations related to dissipation in the Moon with an accuracy better than 1mas

- Is there a core in the Moon ?
- Is the core metallic ?
- Is the metallic core liquid ?
- Is there an inner core center of the liquid core ?

## Other objectives

- First stage of lunar telescope ( technology )
- Establishment of a lunar coordinate system

Molten core ?      Solid inner core ??



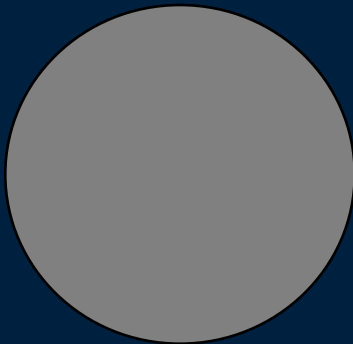
# Moment of inertia is the key for the core existence



Thin spherical shell

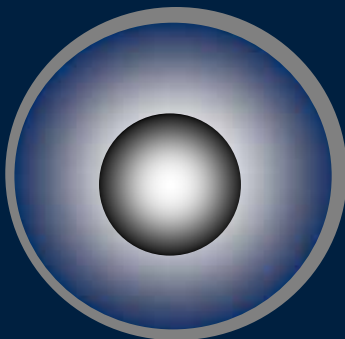
$$\frac{2}{3}$$

$$I = \square MR^2$$



Uniform density

$$\frac{2}{5} = 0.4$$



Metallic Core

$$< \frac{2}{5}$$

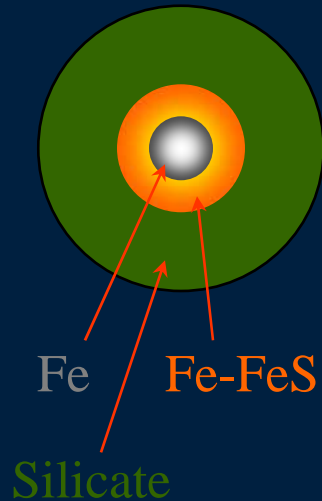


(K. Heki)

# Moment of inertia was the key to study their interiors

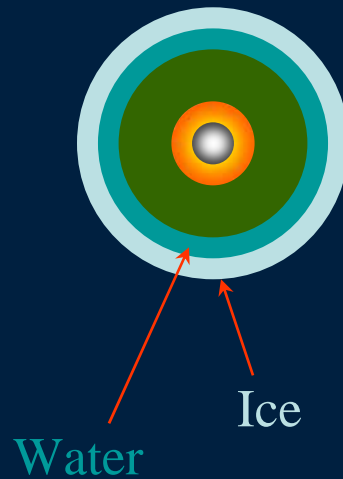
Io

$$C/MR^2=0.378$$



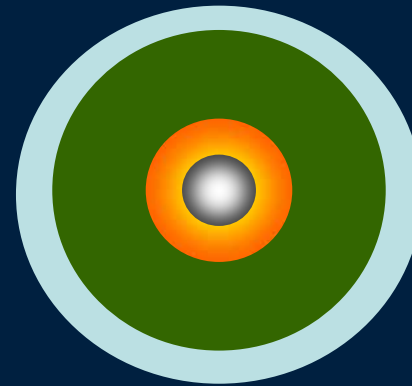
Europa

$$C/MR^2=0.330$$



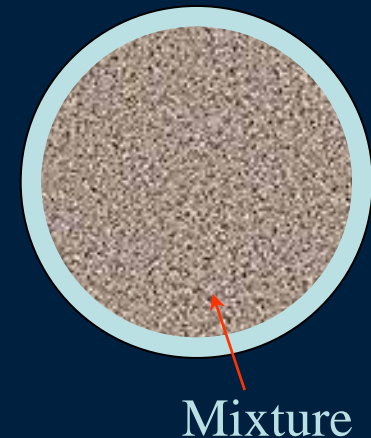
Ganymede

$$C/MR^2=0.3105$$



Callisto

$$C/MR^2=0.406$$



## Galilean satellites

inner



outer

(K. Heki)

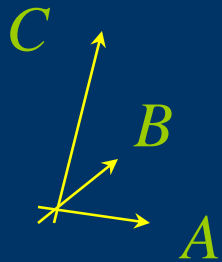
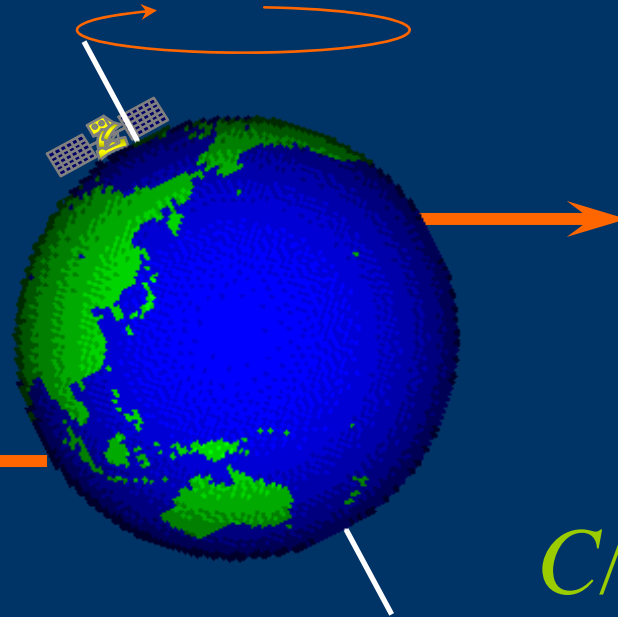
# Combination of $J_2/C_{22}$ and $H$ gives MOI

Forced nutation  
 $H=(C-A)/C$

from LLR  
-> ILOM

Orbit perturbation  
 $J_2=(C-A)/MR^2$

from Clementine, LP,...



Moment of Inertia

$$C/MR^2 = J_2/H$$

Earth : 0.334

Moon :  $0.3929 \pm 0.0009$

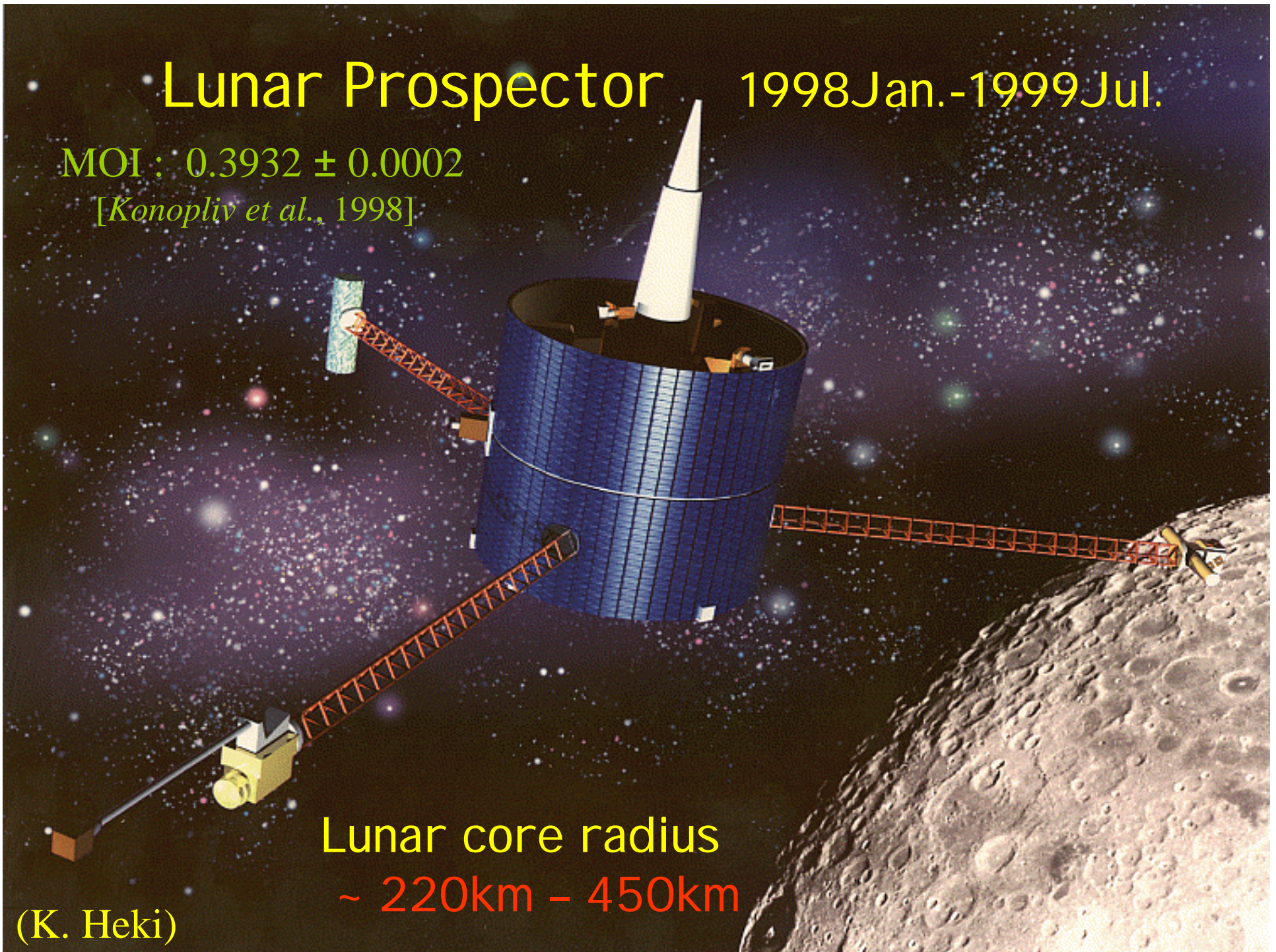
[Williams et al., 1996]

(K. Heki)

# Lunar Prospector 1998 Jan.-1999 Jul.

MOI :  $0.3932 \pm 0.0002$

[*Konopliv et al., 1998*]



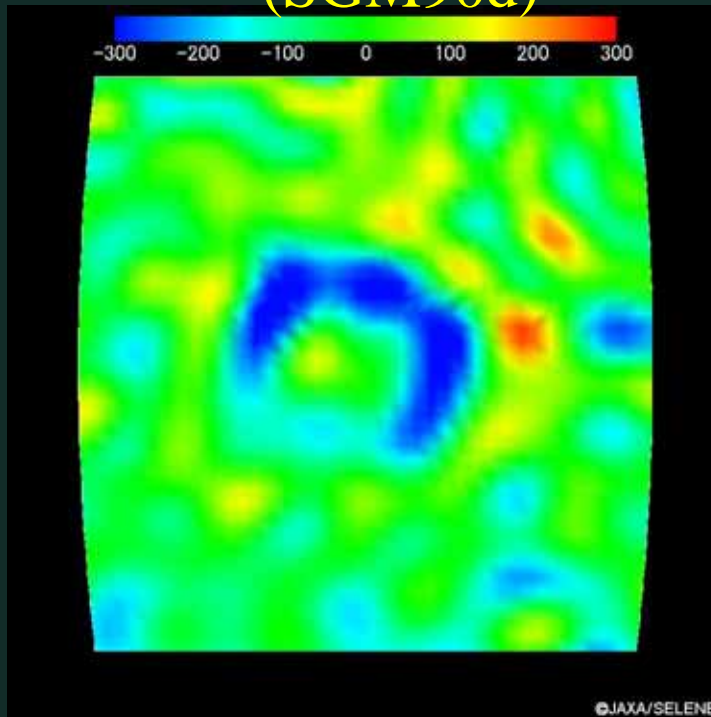
Lunar core radius  
~ 220km - 450km

(K. Heki)

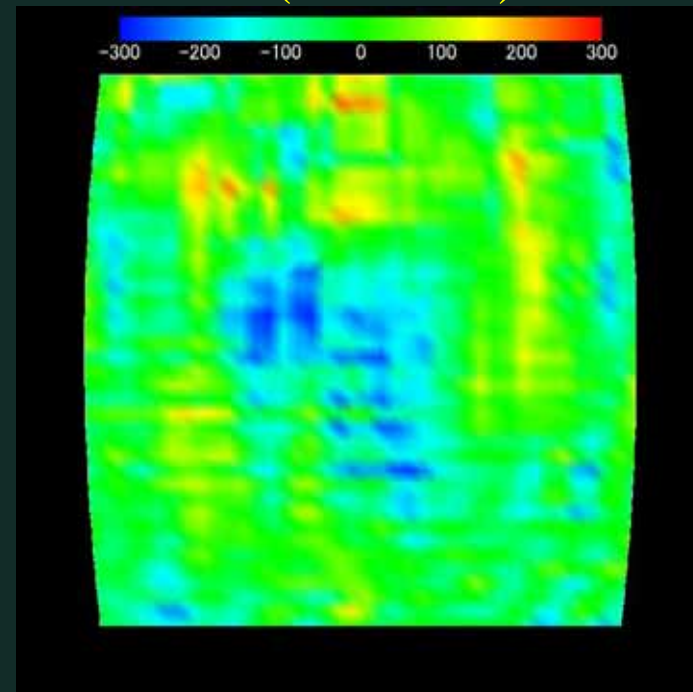
# Kaguya (SELENE)

2007Oct. -2009

(SGM90d)



(LP165P)



[http://wms.selene.jaxa.jp/index\\_e.html](http://wms.selene.jaxa.jp/index_e.html)

lower degrees coefficient  
coming soon !

# Development of BBM

CCD

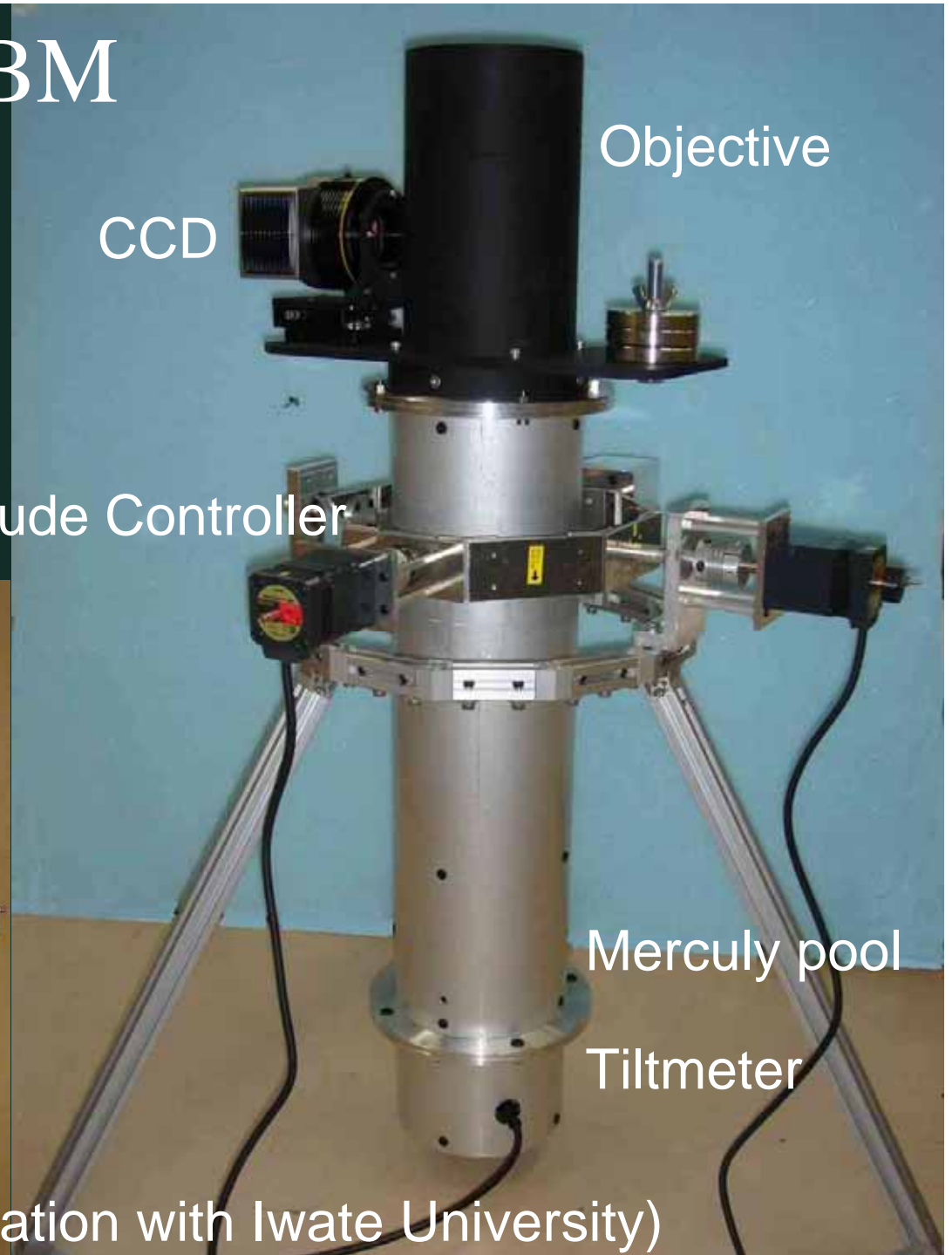
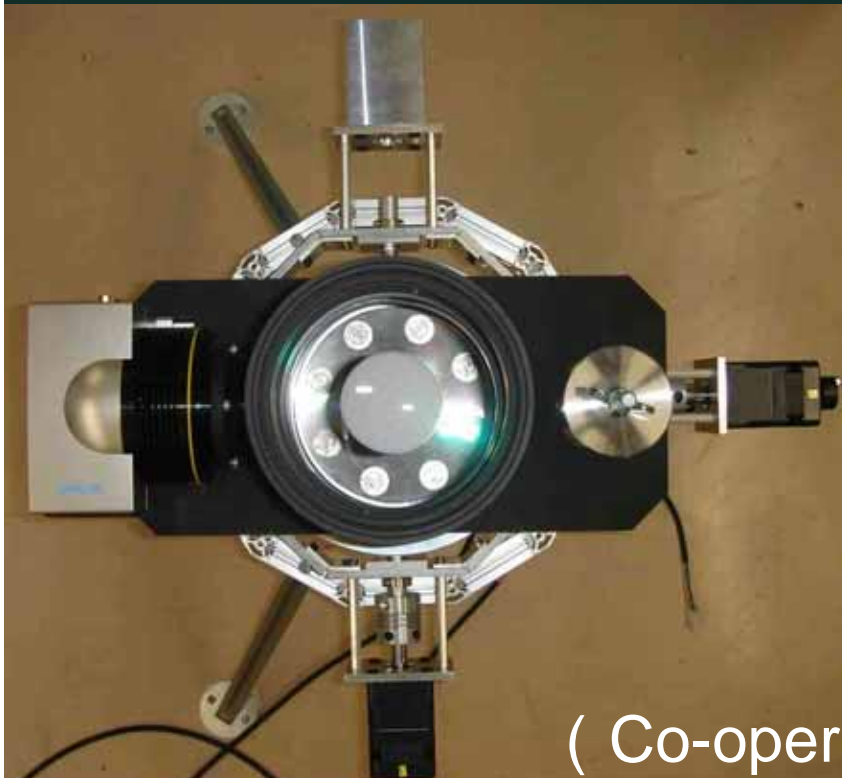
Objective

Attitude Controller

Mercury pool

Tiltmeter

( Co-operation with Iwate University)



# Specifications

Aperture	0.2m
Focal Length	2m
Resolving Power	1" (@500nm)
Detector	CCD
Dimension of a Pixel	9mm × 9mm
Number of Pixels in an Array	4,096 × 4,096
Field of View	1° × 1°
Integration Time	10s
Magnitude of Target Stars	M < 12

# Roadmap of Lunar Observatory

2007-09 Kaguya (SELENE)

2014? SELENE-2

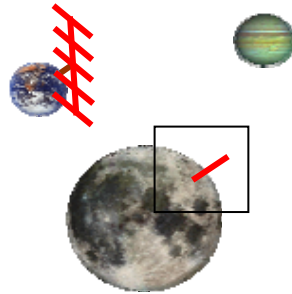
20XX

1<sup>st</sup> Step

- LRS RF observation
- Radio occultation for ionospheric study



Moon-Earth Interferometer



Small-scale Interferometer



Large-scale Interferometer

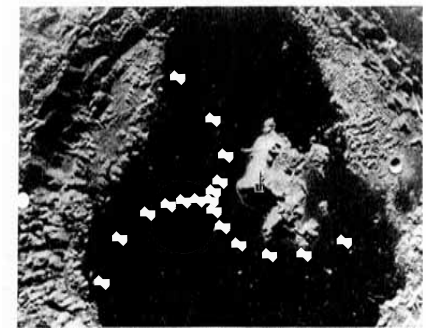
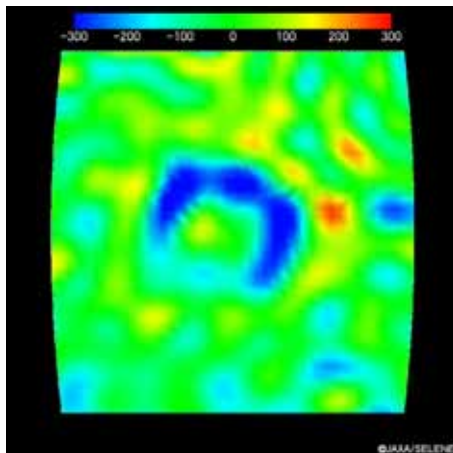
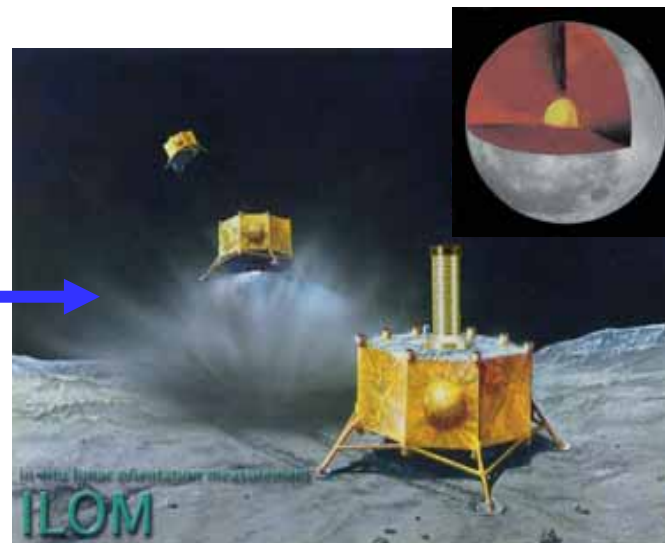
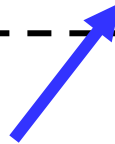


Fig. 4 - The possible locations for array on lunar far side within the crater Daikoku. The circle is about 20 km diameter.

- far-side / improvement of low-degree gravity field
- precise topography

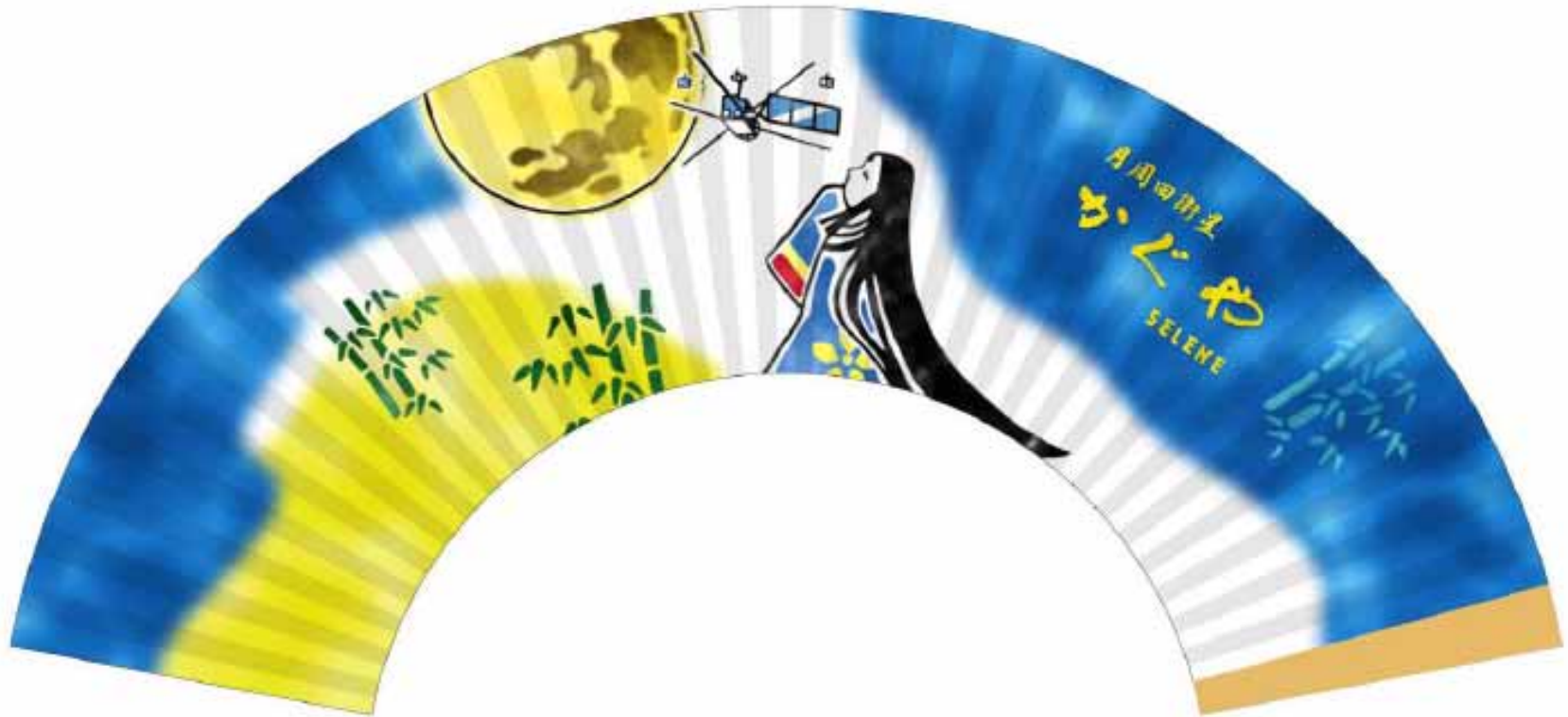


- inner core state/existence
- technological development



toward large-scale optical telescope





Thank you for your attention