# Probing planetary interiors by spacecraft orbital observations

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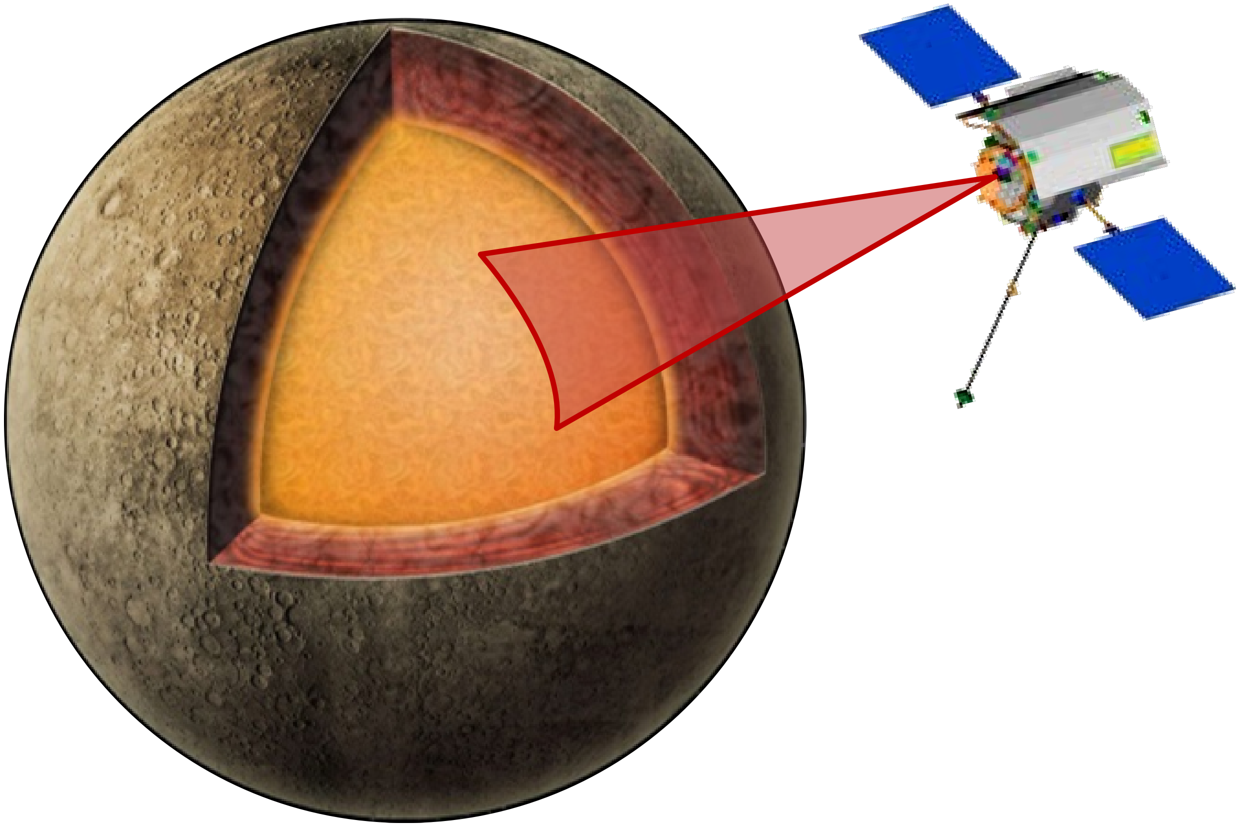

Image credit: NSF/ NASA/JHU APL/ CIW

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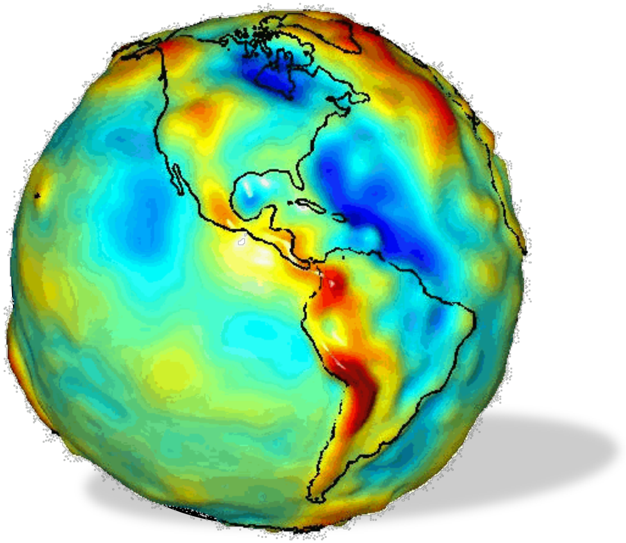
# Introduction

- How to study interiors of terrestrial planets and satellites?
  - Seismicity
  - Gravity field
  - Radar Sounding
  - **Rotation**
  - **Tidal deformation**



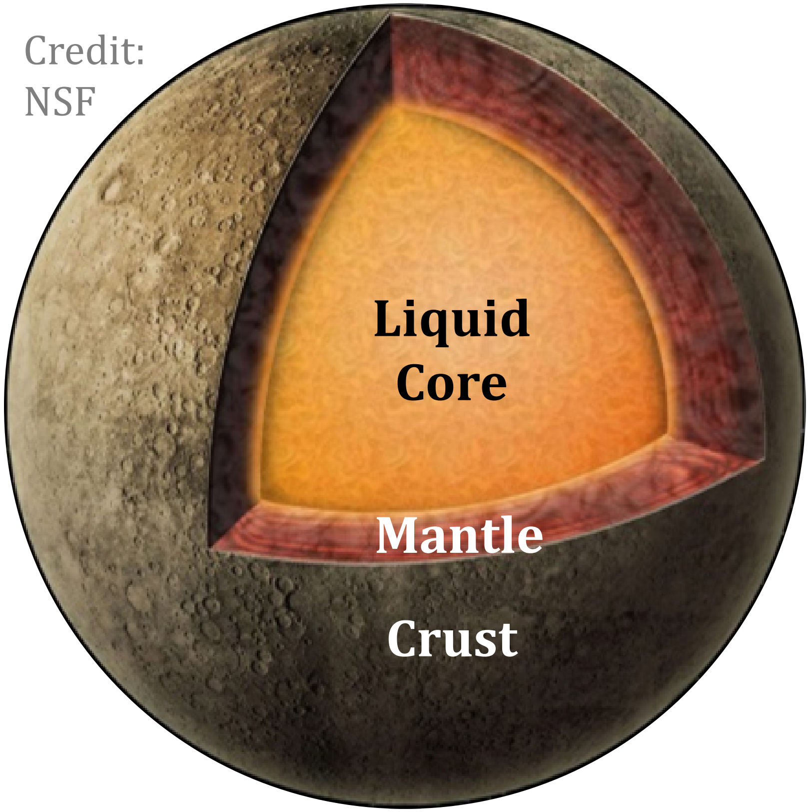
Gravity anomalies in Earth's gravity field from GRACE data (Credit: NASA)

- Which instruments can be used?
  - Seismometer (*Apollo@Moon* | *InSight@Mars*)
  - Radio Science (*GRACE@Earth* | *GRAIL@Moon*, etc.)
  - Subsurface Radar (*RIME@JUICE*)
  - **Laser Altimeter** (*MESSSENGER@Mercury* | *LRO@Moon*)
  - **Cameras** (*Dawn@Ceres/Vesta* | *Rosseta@GC*)

# Introduction

- Objects under study:

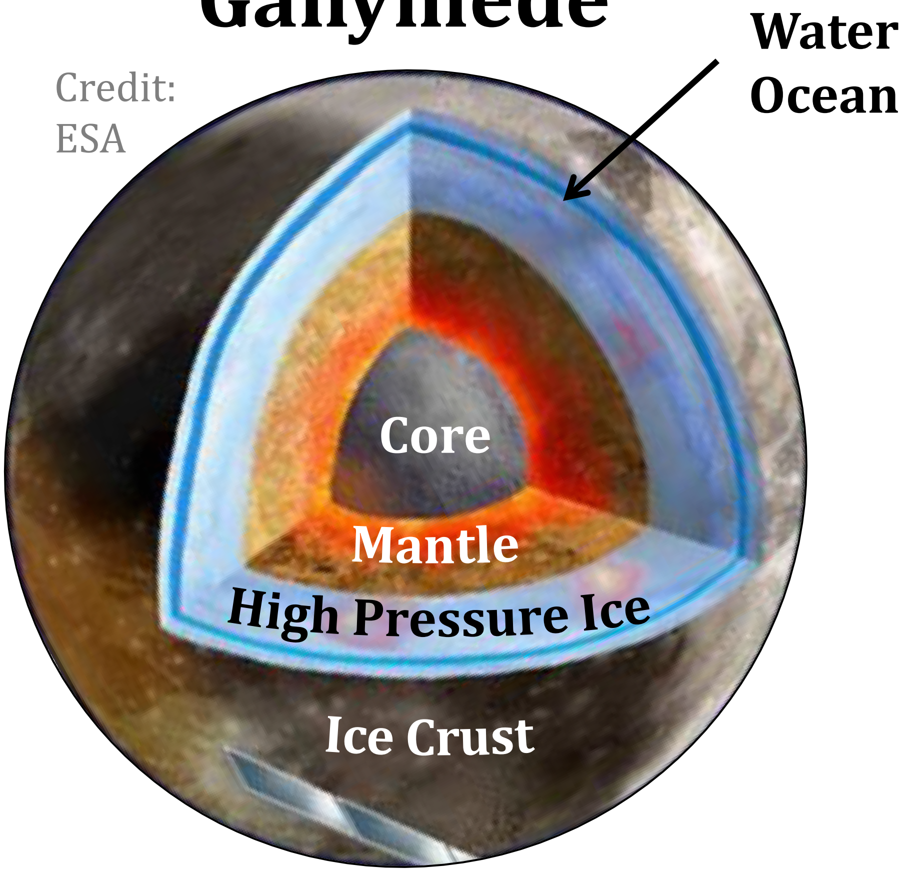
## Mercury



Credit: NSF

Radius = 2439.4 km
(Perry et al., GRL, 2015)

## Ganymede



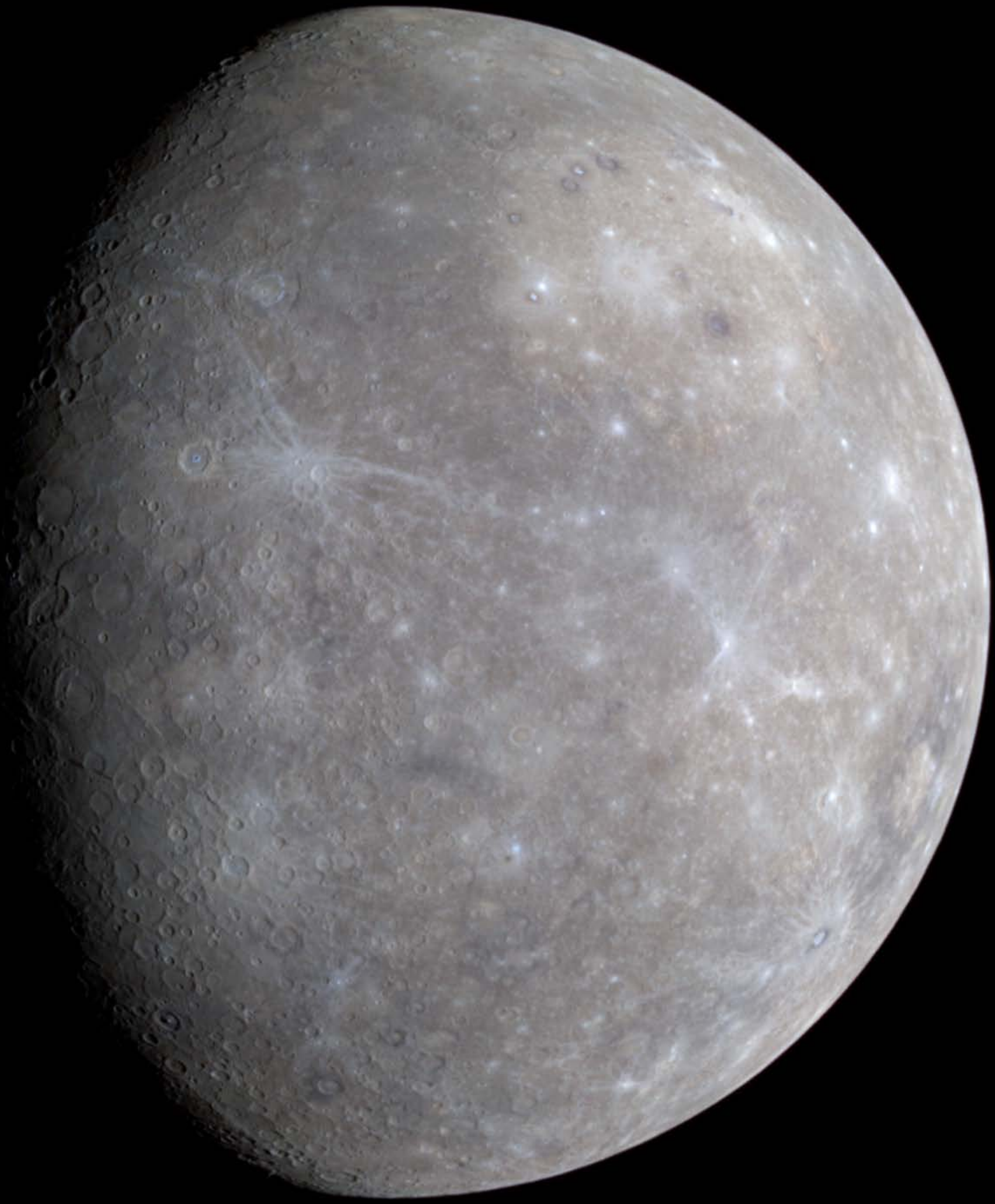
Credit: ESA

Radius = 2632.6 km
(Zubarev et al., PSS, 2015)

# Mercury

# Mercury

Mercury color image, MESSENGER FlyBy 1 (14.01.08)
Image credit: NASA/JHU APL/ CIW



- spacecraft observations:

  Mariner 10 & MESSENGER

- high density:

  5425 kg/m$^3$

- dipole magnetic field
- distance to Sun:

  46 – 70 Mio. km

- orbital period

  88 days

- rotation period

  59.6 days

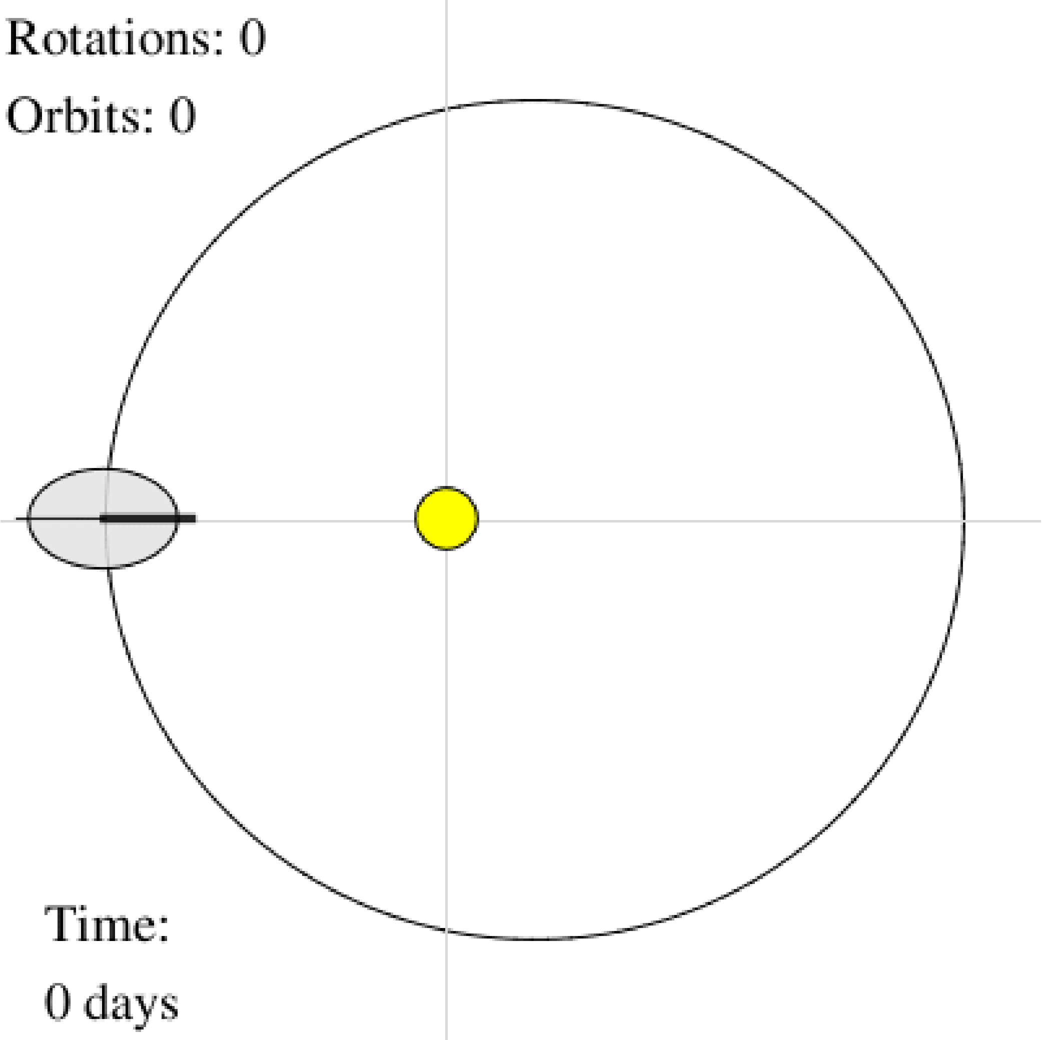
# Mercury

## 3:2 Spin-orbit resonance

- rotation is coupled to the orbital motion through strong tidal torque exerted by the Sun

3 × rotation period
= 2 × orbit period

3 × 58.65 days
= 2 × 87.98 days

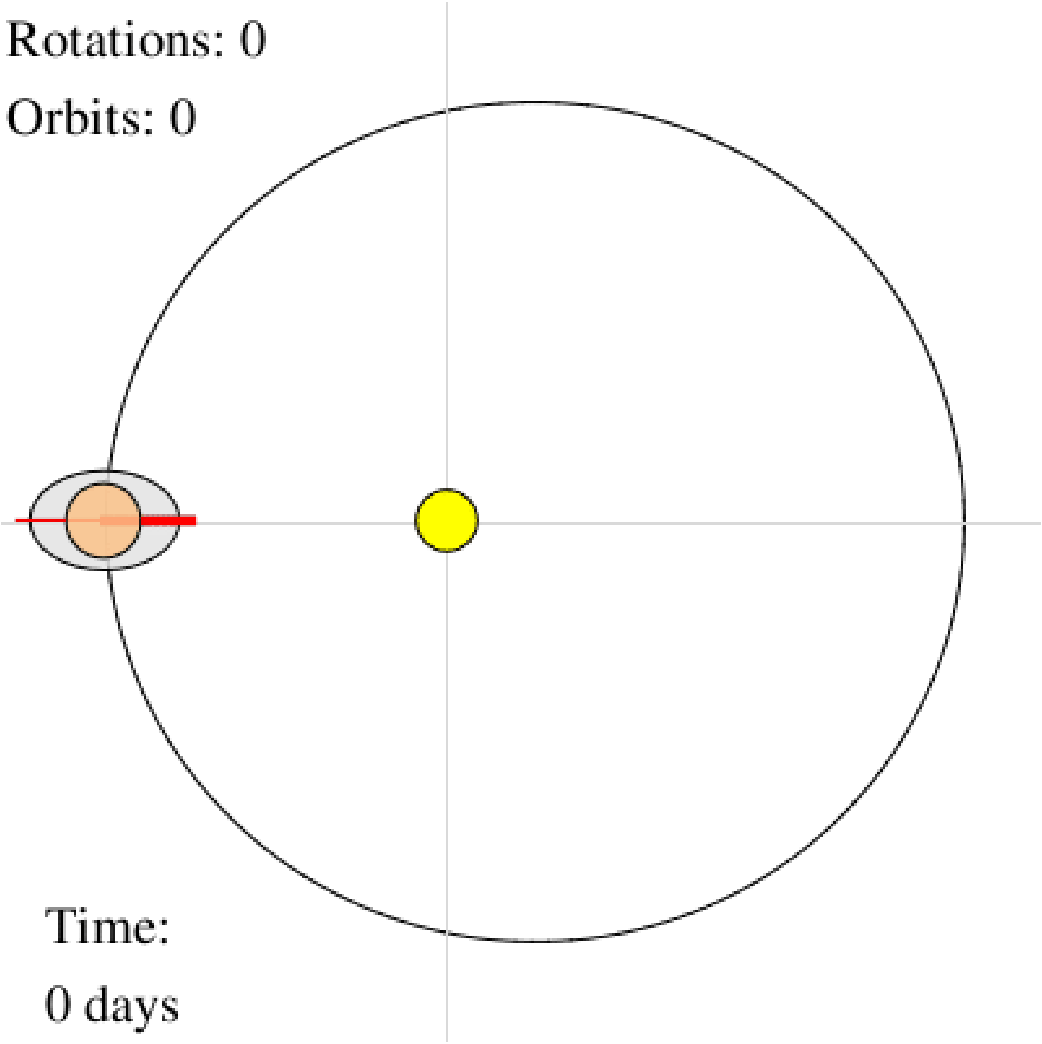


# Mercury

## Longitudinal Librations

- Small librations (rotational oscillations) in longitude on orbital period
- Mantle (black line) is in some places ahead or lagging the uniform rotation of the core (red line)
- Amplitude of librations linked to interior structure (450 m at equator)

→ High libration amplitude indicates decoupled mantle and core



# Mercury

## Peale’s Experiment

- Peale experiment (devised almost a half century ago by Stanton J. Peale, Icarus, 1972)

- inference of Mercury’s interior from measurements of its gravity field and rotation by an orbiting spacecraft

- relevant rotational parameters are the amplitude of physical librations, the obliquity of rotation axis, and gravity field asymmetry

$$\left(\frac{C_m}{B-A}\right)\left(\frac{B-A}{MR^2}\right)\left(\frac{MR^2}{C}\right)=\frac{C_m}{C}<1$$

libration amplitude × gravity field × obliquity spin axis

$A < B < C$
principal axes of inertia of the planet

$C_m$
polar moment of inertia of the mantle

# Mercury

## MESSENGER Mission

- NASA Discovery Mission
- orbit insertion: 18.03.2011
  (after a 6 year journey)
- first s/c orbiting Mercury
  (Mariner 10 flybys in 1974)
- 4 years of operation (04.2015)
- elliptic, polar orbit
- 7 scientific instruments
    **MDIS** (**M**ercury **D**ual **I**maging **S**ystem)
    **MLA** (**M**ercury **L**aser **A**ltimeter)

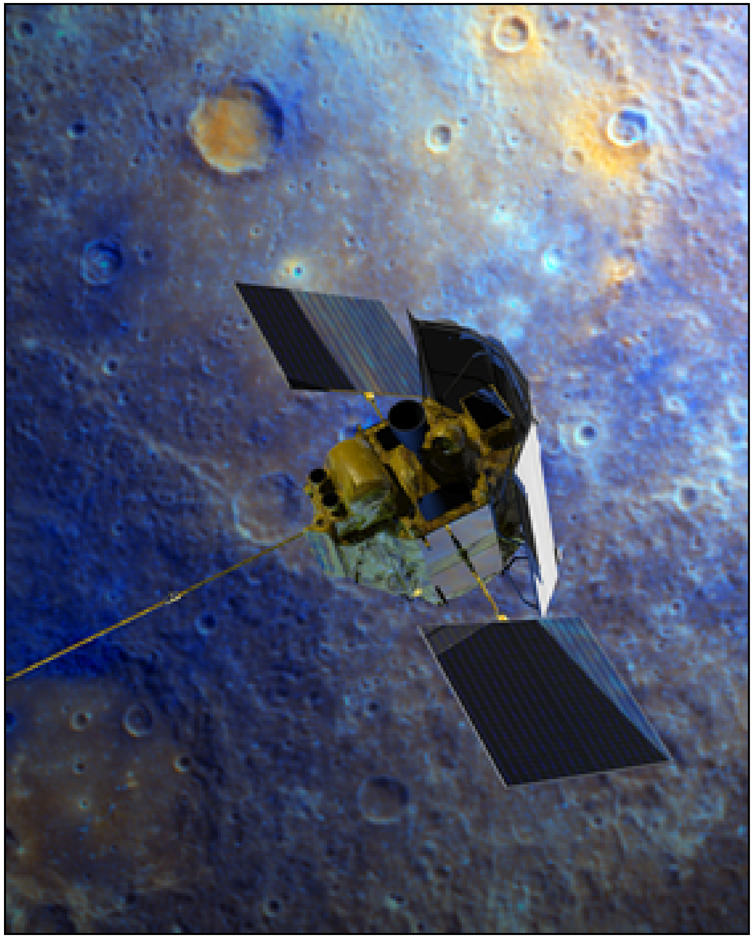
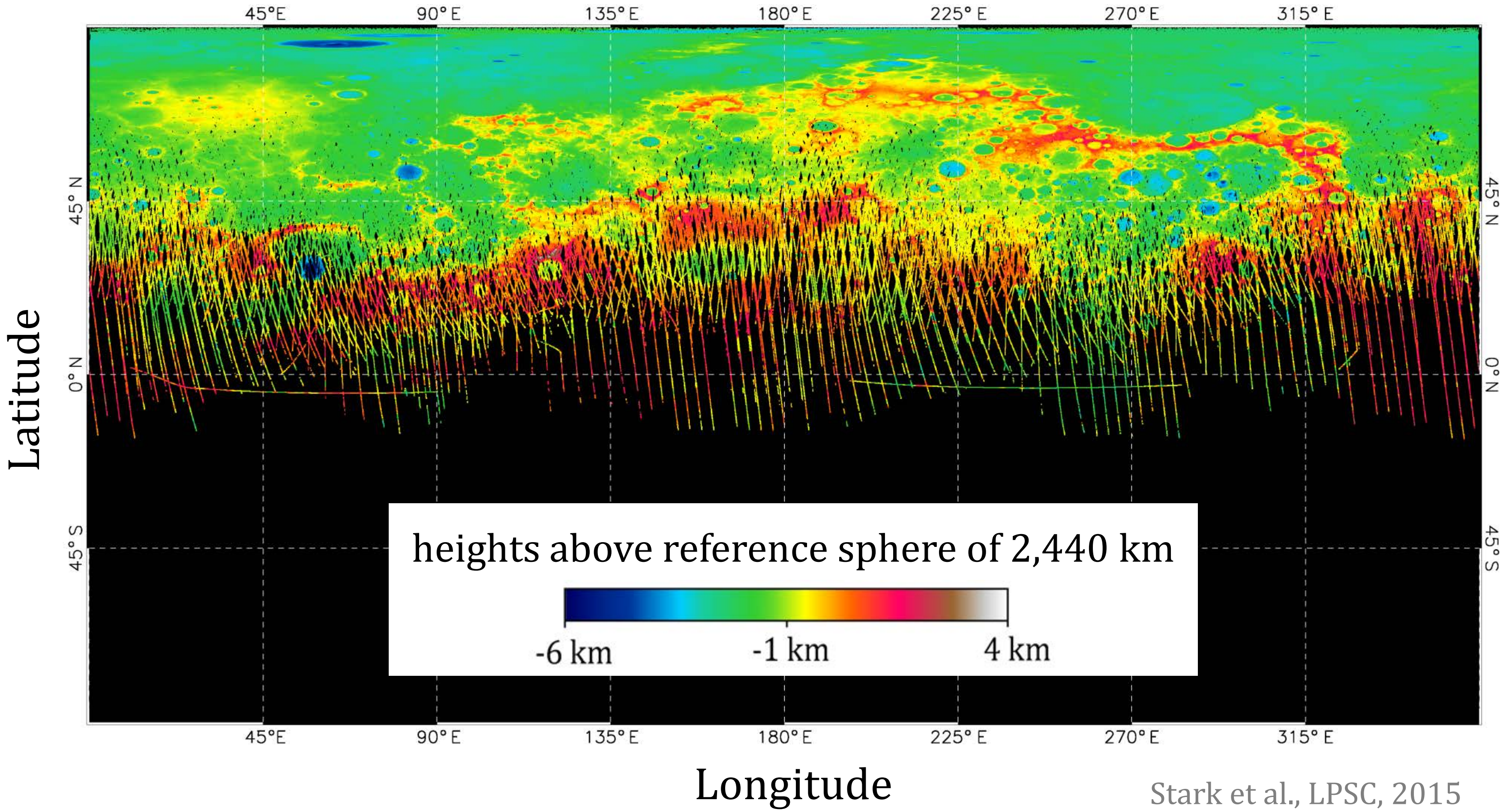


Image credit: NASA/JHU APL/ CIW

# Mercury

## MESSENGER Data – Mercury Laser Altimeter

- coverage after 3 years of observations

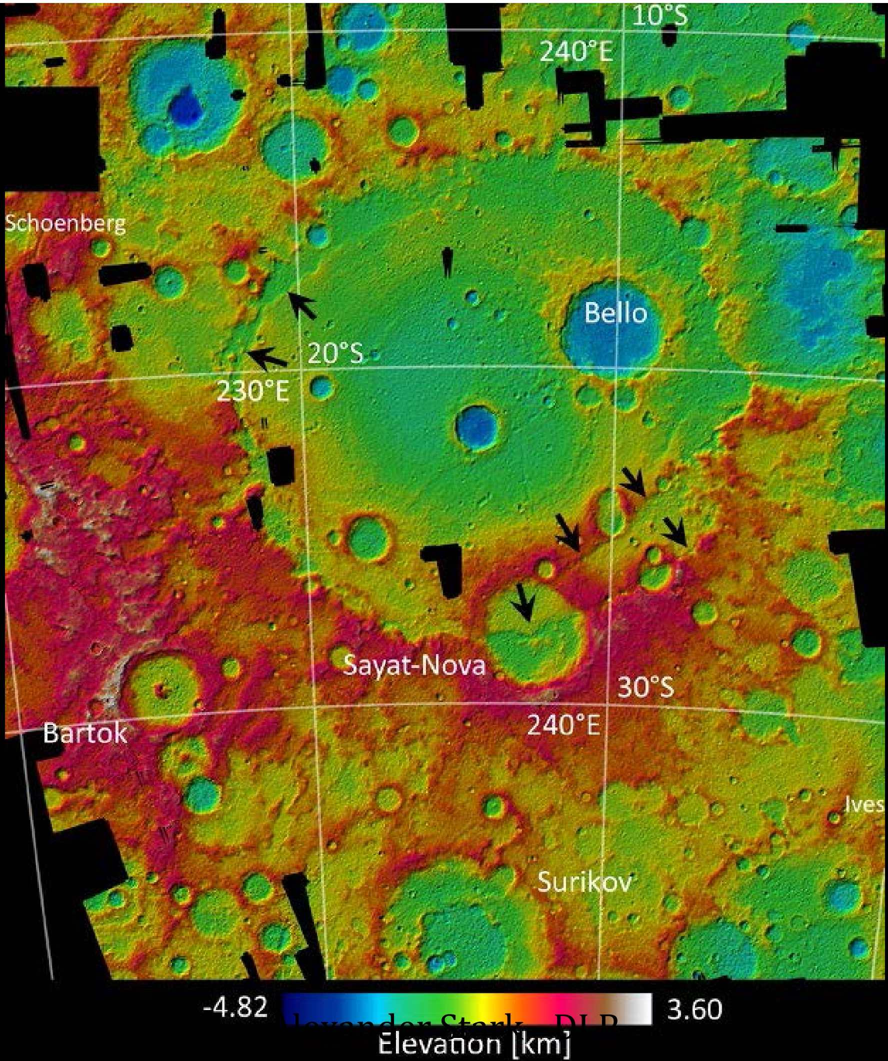


Stark et al., LPSC, 2015

# Mercury

## MESSENGER Data – Imaging System

- Beethoven Basin

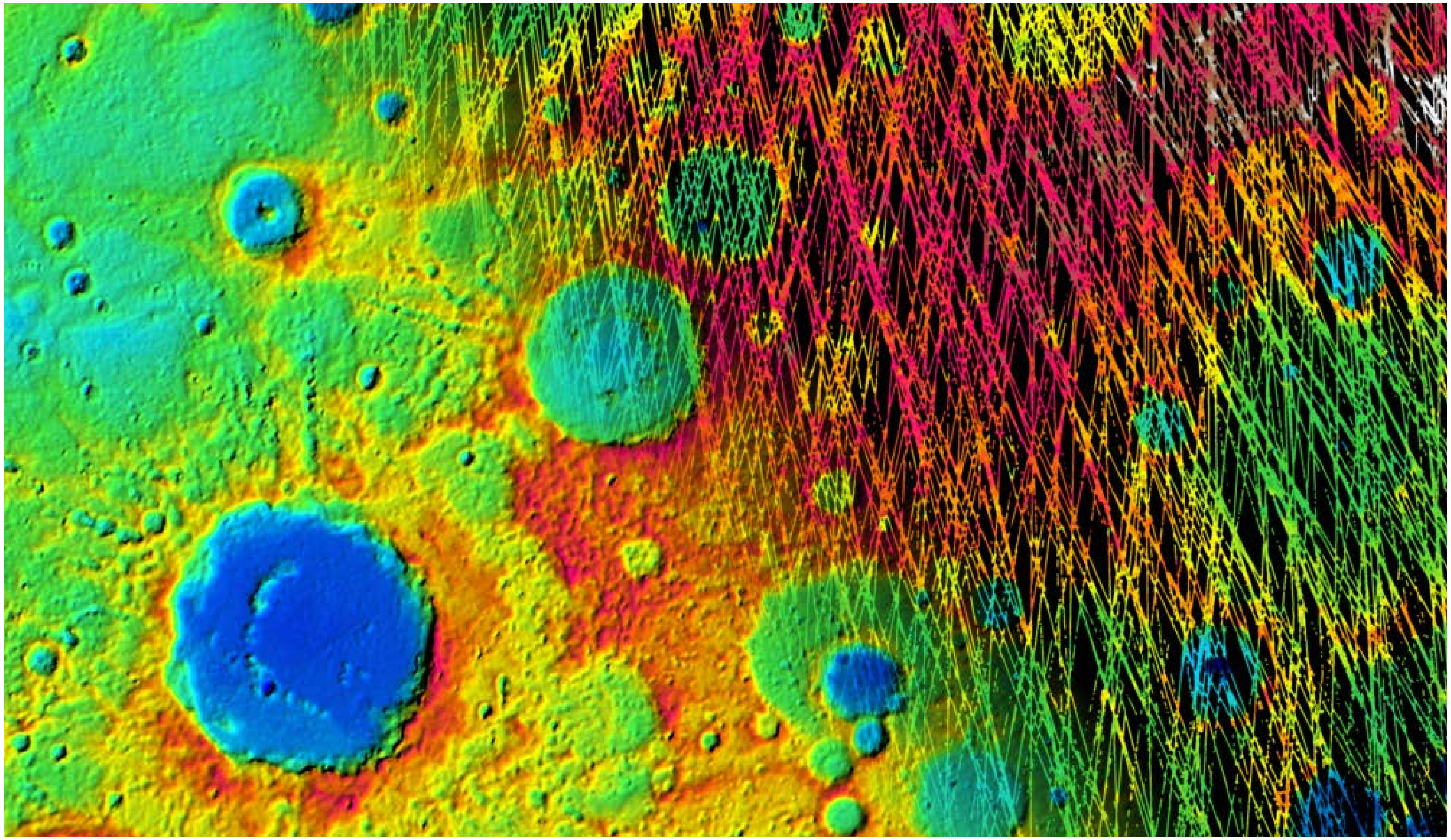


Preusker et al., LPSC, 2012

# Mercury

## Co-registration Method

- laser altimeter profiles and digital terrains models derived from stereophotogrammetry (stereo DTMs) form complementary data sets



Stark et al. GRL, 2015

# Mercury

## Co – registration method

- minimization of height differences between laser spots $r_{\mathrm{LA}}$ and stereo DTM $r_{\mathrm{DTM}}$ in a least-squares sense

$$\sum\left[r_{\mathrm{DTM}}(\lambda_{\mathrm{LA}}(\boldsymbol{p}),\phi_{\mathrm{LA}}(\boldsymbol{p}))-r_{\mathrm{LA}}(\boldsymbol{p})\right]^{2}\rightarrow\mathrm{min.}$$

DTM heights @ location of laser spot – laser spot heights

- weighting of observations by the uncertainty of laser altimeter measurement (spacecraft altitude, off-nadir pointing)
- non-linear model is solved iteratively until improvement in the RMS height residuals was at the centimeter level

# Mercury

## Rotational parameters

| rotational parameter | literature value | Stark et al., 2015 (Celest. Mech. Dyn. Astr.) [predicted] | Stark et al., 2015 (GRL) [measured] |
|---|---|---|---|
| rotation rate | 6.1385025 °/day [a] | $\mathbf{6.1385068\ °/day}$ | $\mathbf{6.13851804°/day}$ |
| obliquity | $2.04 \pm 0.08'$ [b] | - | $\mathbf{2.029 \pm 0.085'}$ |
| libration amplitude | $38.5 \pm 1.6''$ [b] | - | $\mathbf{38.9 \pm 1.3''}$ |

[a] IAU report (Archinal et al., Celest. Mech. Dyn. Astr., 2011)
[b] Earth-based radar (Margot et al., JGR, 2012)

→ Earth-based observations of Mercury's rotation (Margot et al., 2012) could be confirmed

→ Mercury rotates faster than expected! Maybe long-period libration cycle of (12 years) caused by perturbations of Mercury's orbit by Jupiter

# Mercury

## Implications on interior - Moments of inertia

- rotational parameters provide constrains on moments of inertia of the planet
  - from libration amplitude → equatorial asymmetry

$$\frac{B-A}{C_\mathrm{m}} = (2.206 \pm 0.074) \times 10^{-4}$$

  - from obliquity → polar moment of inertia of the whole planet

$$\frac{C}{MR^2} = 0.346 \pm 0.011$$

  - from gravity field (Mazarico et al., JGR, 2014) → $J_2$ and $C_{22}$

→ from all values one can compute the ratio between the polar moment of inertia of the planet and the mantle (Peale's experiment)

$$\frac{C_\mathrm{m}}{C} = 4C_{22}\frac{MR^2}{C}\frac{C_\mathrm{m}}{B-A} = 0.421 \pm 0.021$$

# Mercury

## Implications on Mercury’s interior

- homogeneous layers without compression
- results in agreement with more realistic calculation (Hauck et al., JGR, 2013)

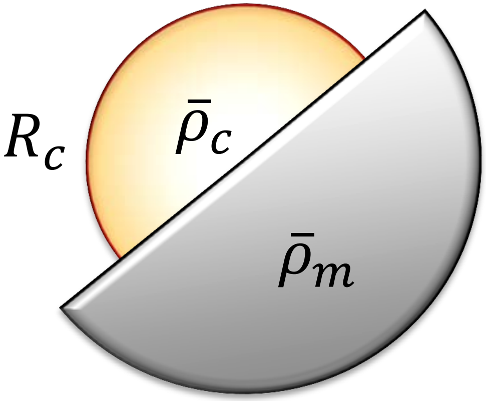
**Input**

**moments of inertia**
$(C/MR^2, C_m/C)$
**bulk properties**
$(M, R)$

→

**Output**

**core radius**
$(R_c)$
**densities of mantle an core**
$(\bar{\rho}_c, \bar{\rho}_m)$



Stark, PhD thesis (2015):

Outer core radius: $R_c = 2008 \pm 52$ km

Density of the core: $\bar{\rho}_c = 7214 \pm 488\ \mathrm{kg/m^3}$

Density of the mantle: $\bar{\rho}_m = 3175 \pm 245\ \mathrm{kg/m^3}$

→ core makes up 70% of mass and about 50% of volume of Mercury

# Ganymede

# Ganymede

Image credit: NASA

- spacecraft observations:

  Voyager & Galileo

- low density:

  1939 kg/m$^3$

- dipole magnetic field
- distance to Jupiter:

  1 Mio. km

- orbital and rotation period:

  7.15 days

01.05.2016

# Ganymede

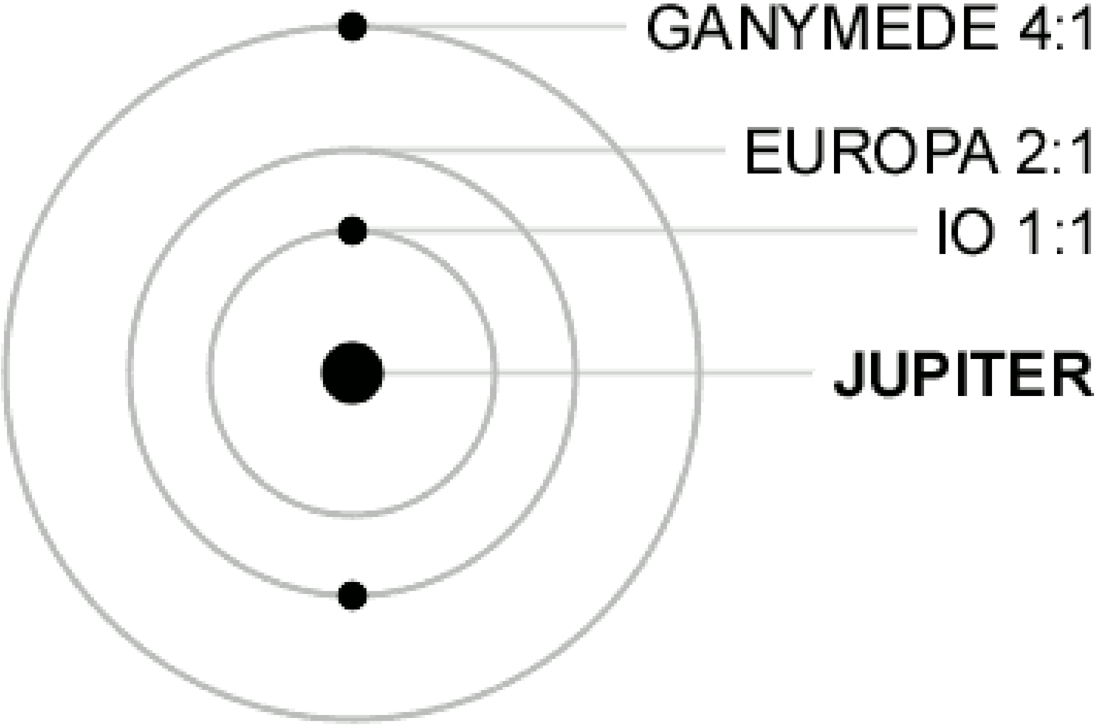
## Laplace resonance

- Coupled orbital motion of Jovian moons

Ganymede: 1 revolution
= Europa: 2 revolutions
= Io: 4 revolutions

- Forced eccentricities of Io and Europa

- High tidal dissipation in interior → volcanism on Io, water oceans on Europa and Ganymede?



Credit: Wikimedia Commons

# Ganymede

## Tides

- Moon's shape deforms during one orbital cycle

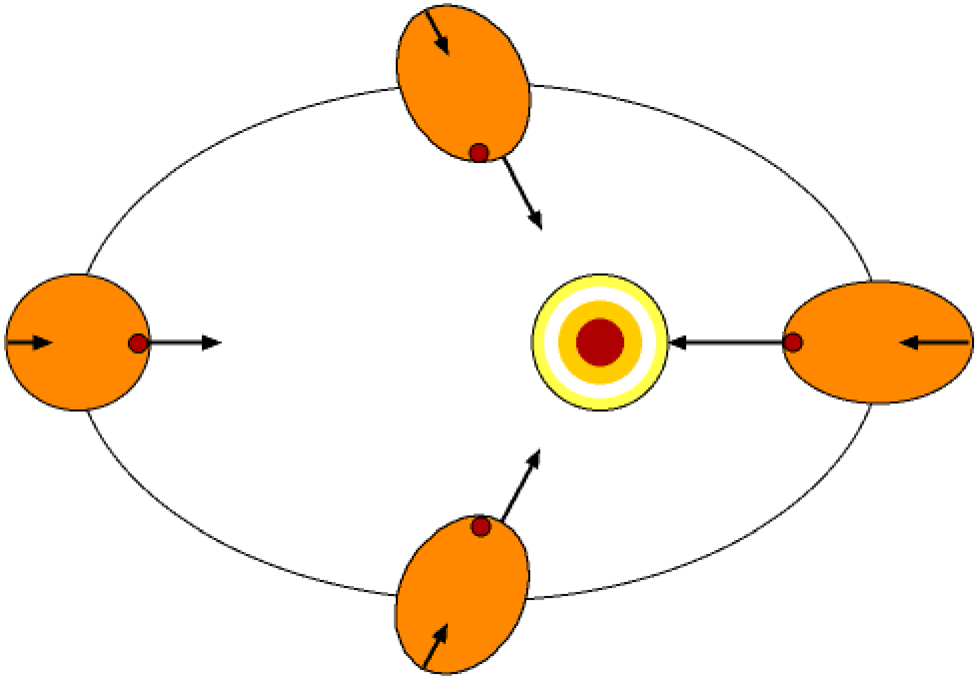
- Deformation can be expressed in terms of Love numbers:

  $k_2$: gravity field variation

  $h_2$: shape deformation

  $l_2$: horizontal deformation

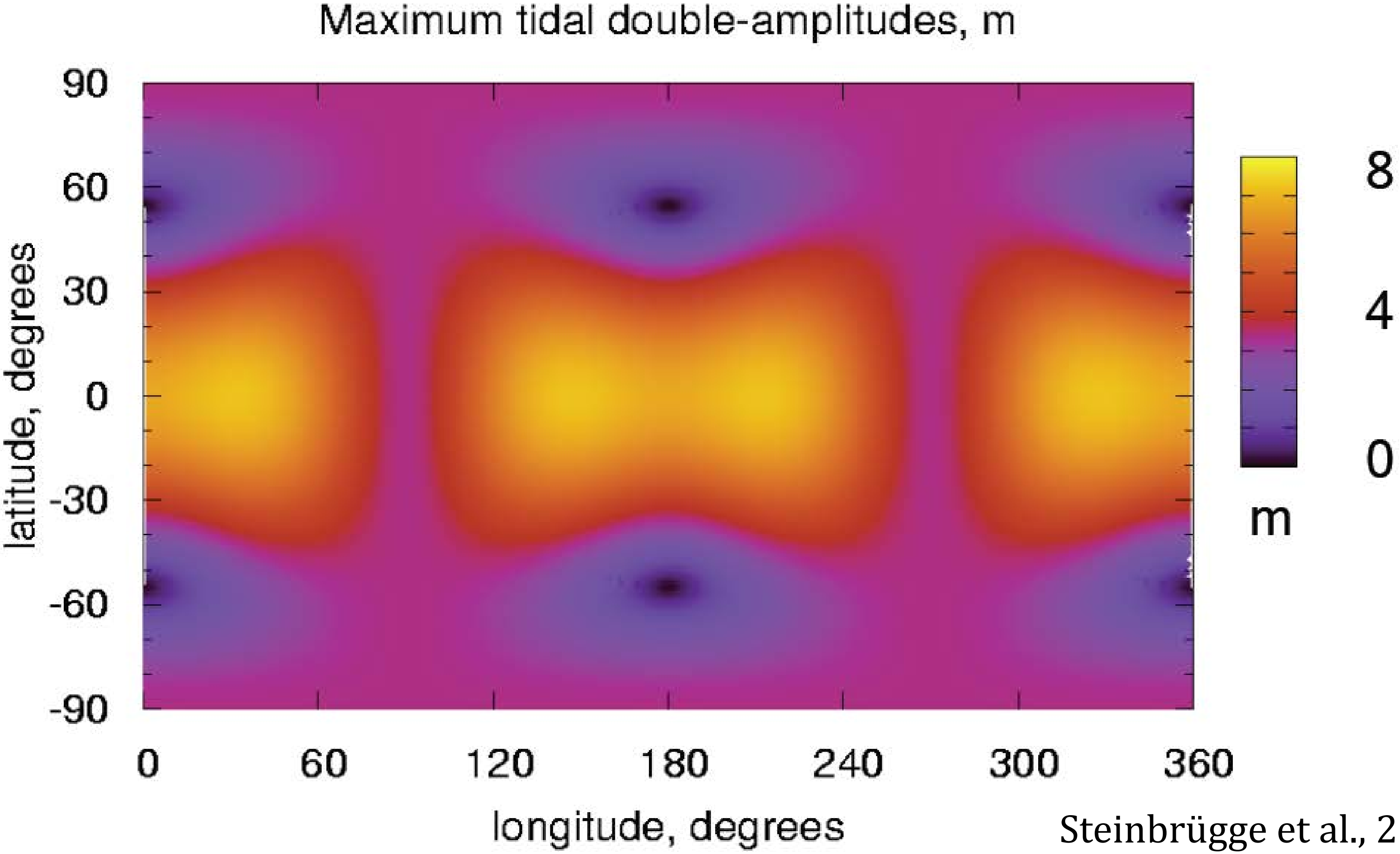
- measurement of the tidal amplitude gives Love numbers, which are dependent on interior structure and rheology



Credit: http://www.astronomynotes.com/solarsys/s14.htm

# Ganymede

## Tides



Steinbrügge et al., 2015

# Ganymede

## JUICE Mission (JUpiter ICy moons Explorer)

- ESA L-class mission
- Launch: 2022
- Arrival at Jupiter: 2030
- Ganymede orbit: 2032
  - polar, circular orbit (500 km)
- 11 scientific instruments

  **GALA** (**GA**nymede **L**aser **A**ltimeter)

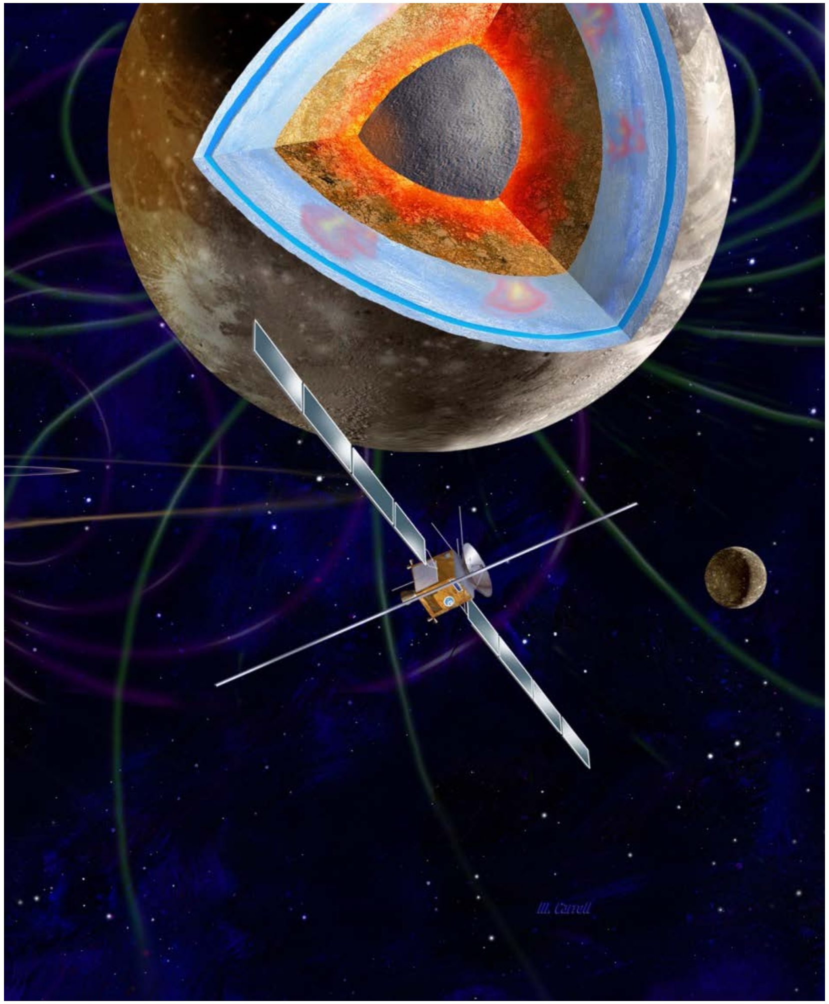
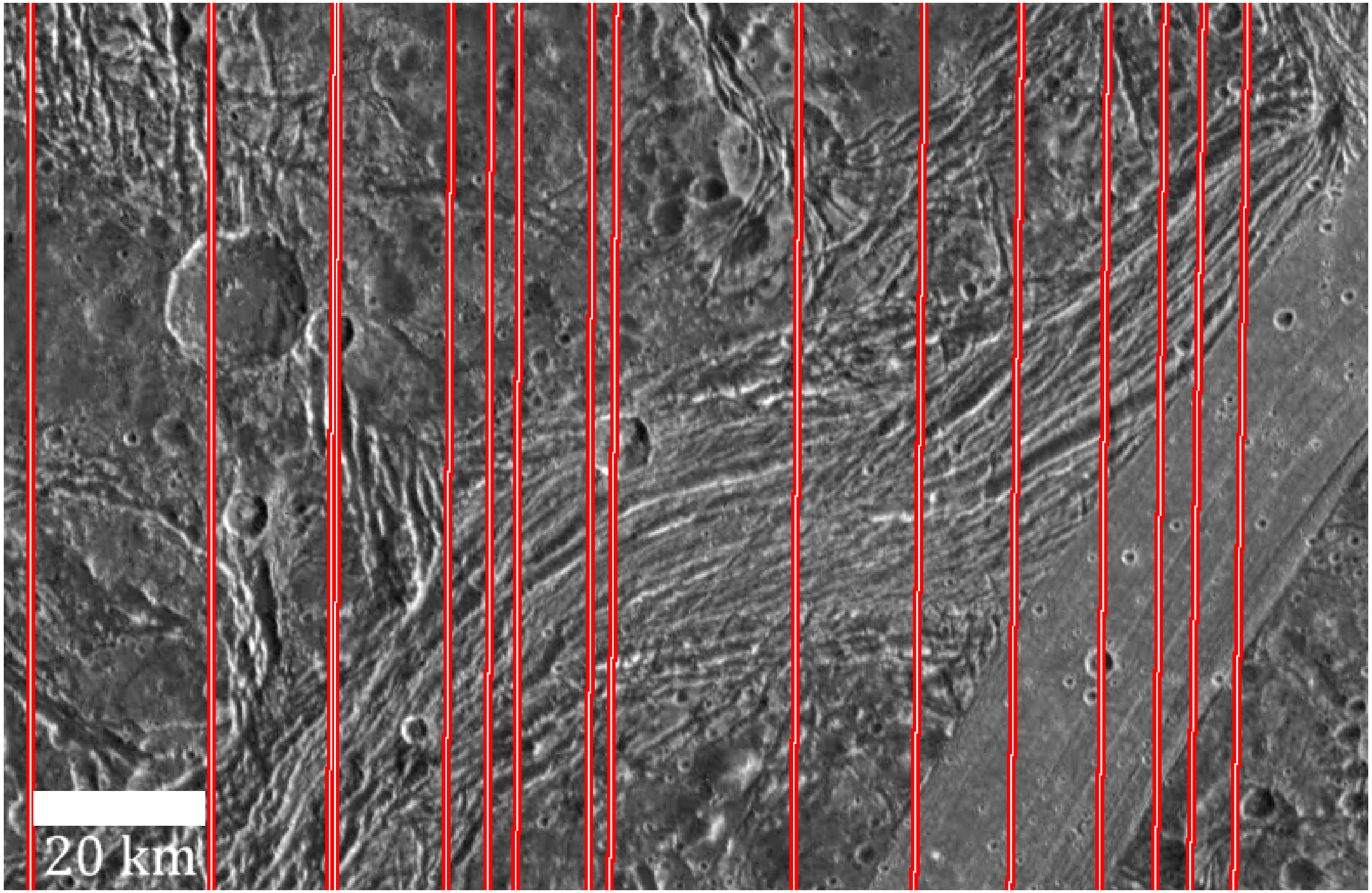


Image credit: ESA

# Ganymede

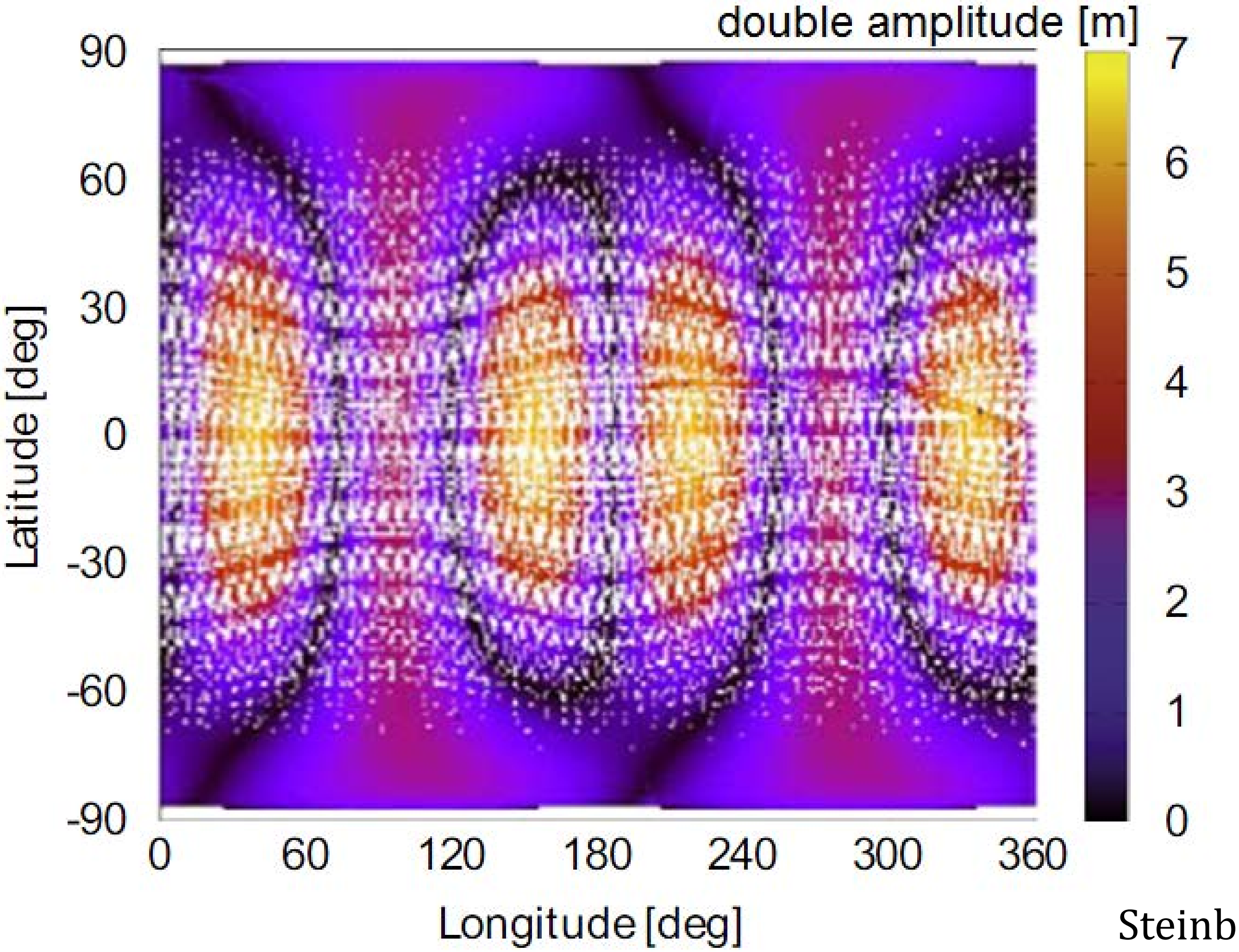
## JUICE Data – Ganymede Laser Altimeter

Image credit: NASA/DLR



# Ganymede

## Laser profiles – Cross over



- $10^5$ cross-over points from about 1000 profiles
- Most cross-overs are at polar regions

Steinbrügge et al., PSS, 2015

# Ganymede

## Measurement of Tidal Amplitude

$$du = \frac{\boxed{h_2}}{g}(\Phi_1(r, \theta, \phi, t_1) - \Phi_2(r, \theta, \phi, t_2))$$

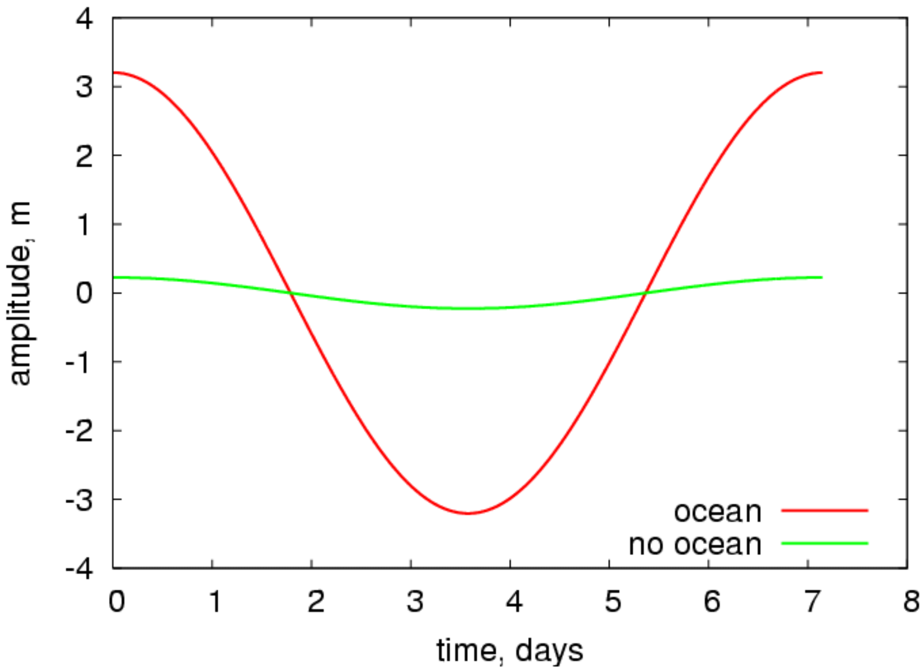
Observed range difference = Tidal potential at t1 — Tidal potential at t2

- uncertainty of $h_2$ measurement:

$$\Delta h_2 = 0.026$$

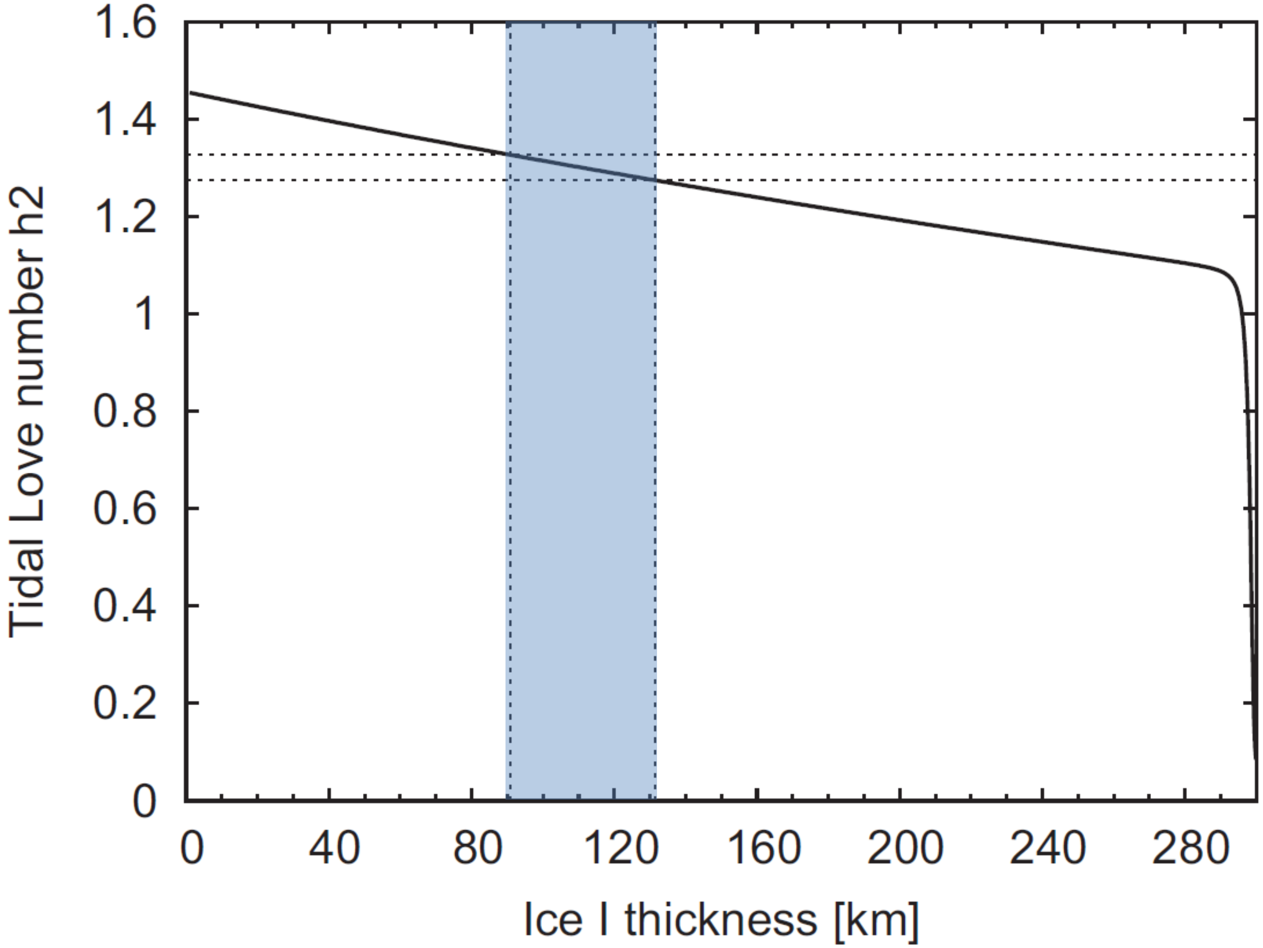
- expected value $h_2$ = 1.3
  → 2 % uncertainty

Steinbrügge et al., PSS, 2015



# Ganymede

## Implications on interior structure



Steinbrügge et al., PSS, 2015

- thickness of the ice shell can be measured to ± 20 km
- confirm existence of water ocean

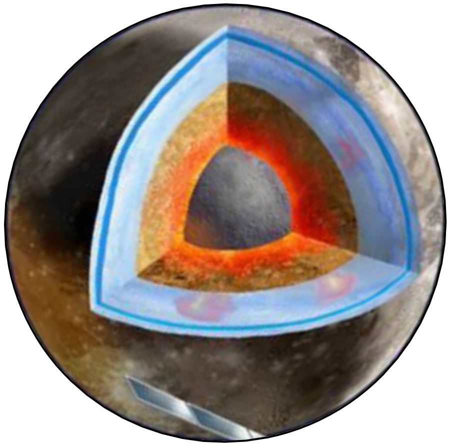


Image credit: ESA

# Thank you for your attention!