Interiors of Vesta and Ceres as constrained by the Dawn mission

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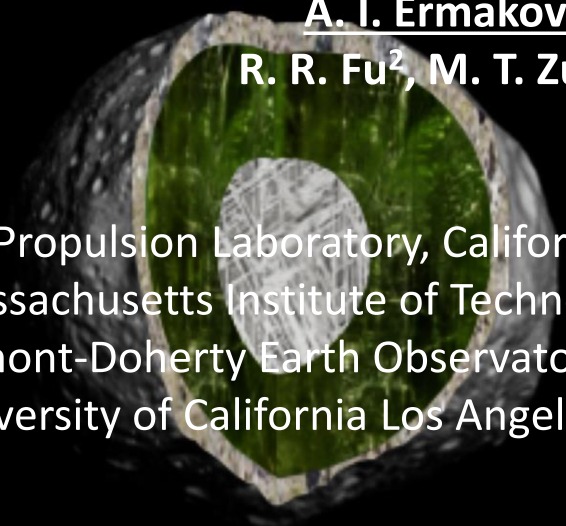
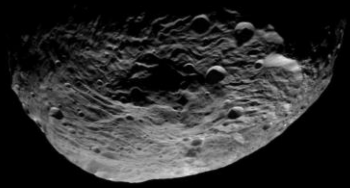
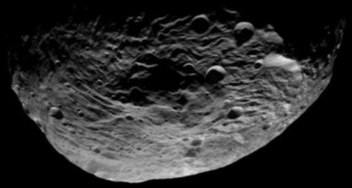
[3]Lamont-Doherty Earth Observatory, Earth Institute, Columbia University
[4]University of California Los Angeles





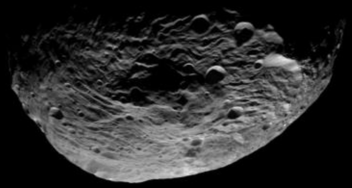
Outline

- State of internal structure knowledge before Dawn
- Data available from Dawn
- Look at gravity and topography spatially
- Look at gravity and topography spectrally
- Compare evolutions of Vesta and Ceres
- Summary of findings



Goal of the talk:

- **Explain how the internal structures of Vesta and Ceres diverged by looking at the present-day gravity and topography measured by Dawn**



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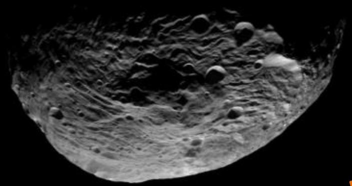
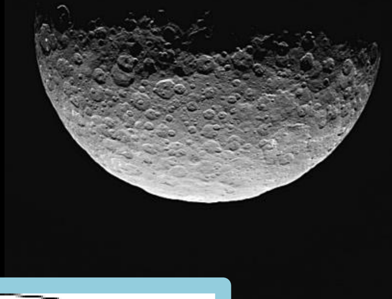
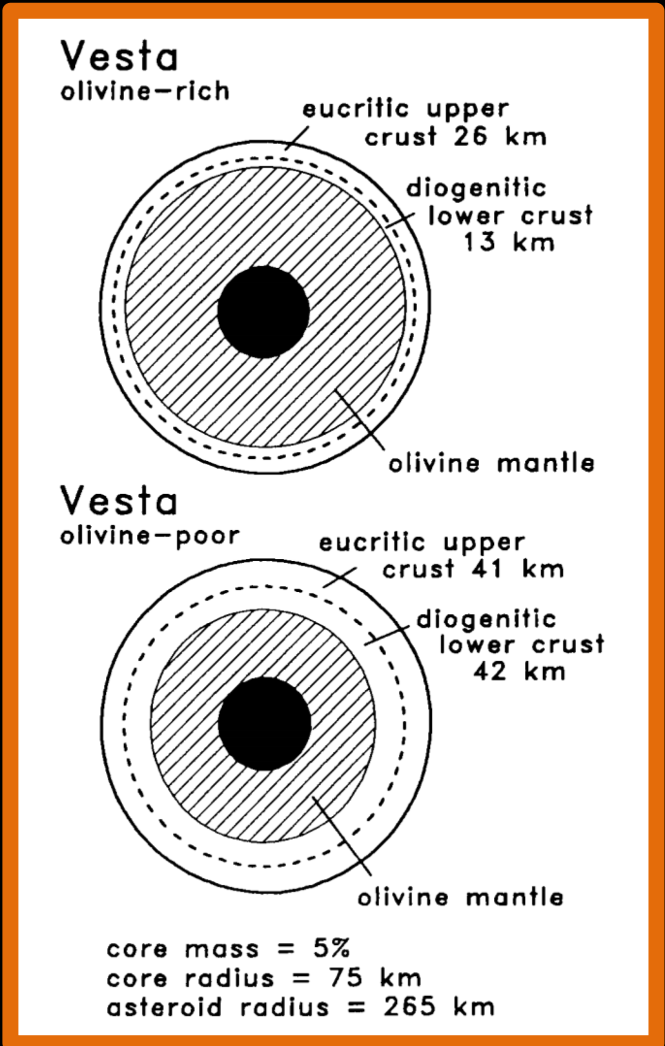


What did we know before Dawn?

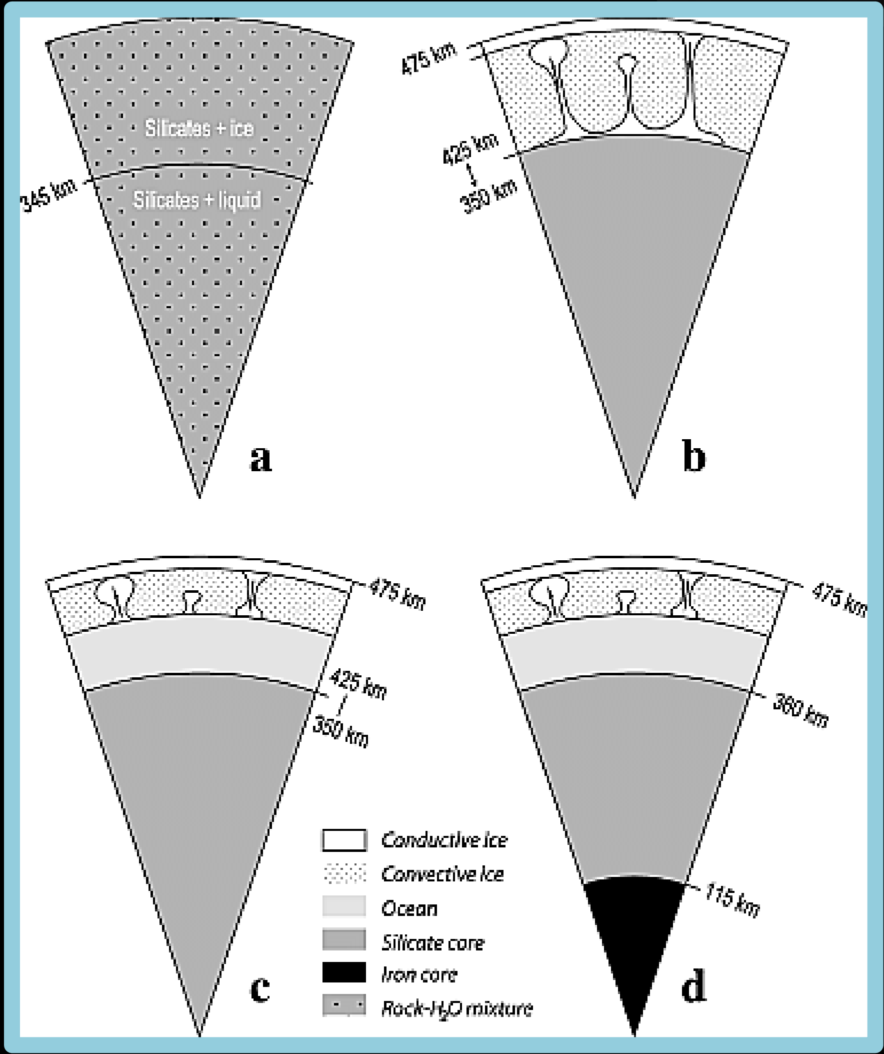


Vesta



Ruzicka et al., 1997

Ceres



McCord and Sotin, 2005

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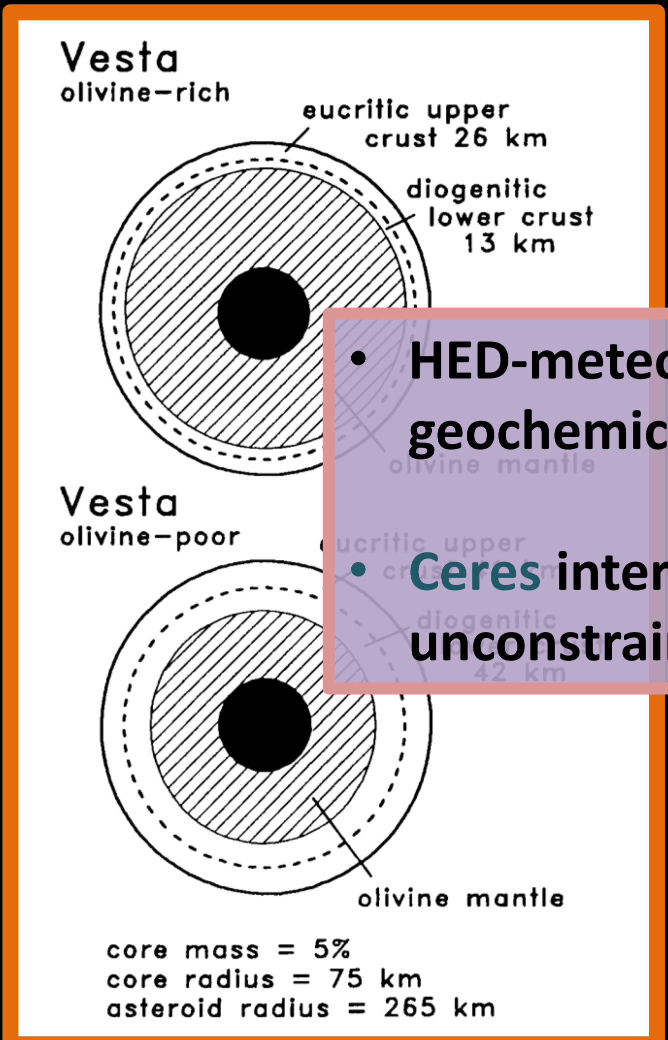

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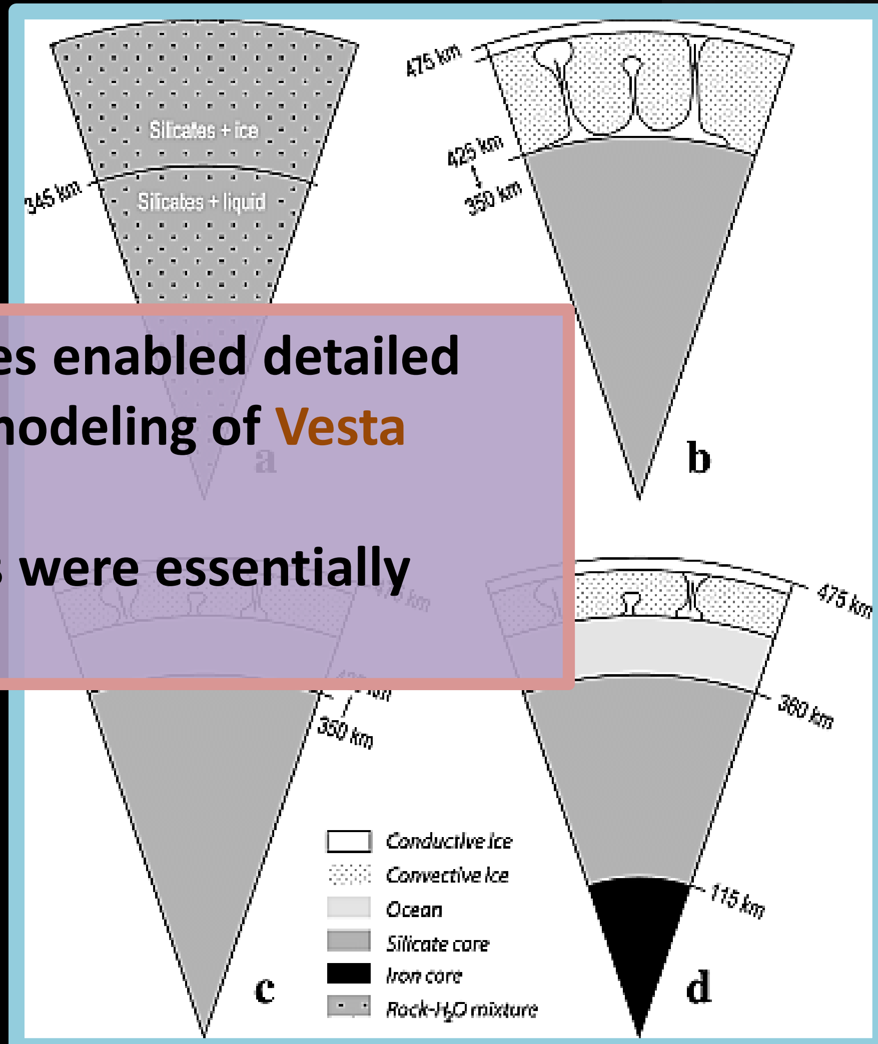
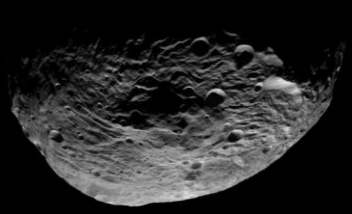


McCord and Sotin, 2005

- HED-meteorites enabled detailed geochemical modeling of Vesta
- Ceres interiors were essentially unconstrained



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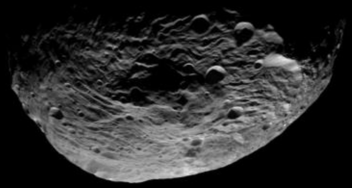
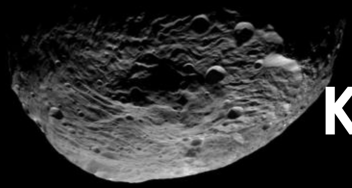


Input for our modeling

- **Gravity field**
  - **Accurate up to *n* = 18 (λ=93 km) for Vesta (Konopliv et al., 2014)**
  - **Accurate up to *n* = 17 (λ=174 km) for Ceres (Konopliv et al., in prep.)**

- **Shape model**
  - **typically reliable up to 1 km spatial scale**

- **Assumptions we have to make:**
  - **Multilayer model with uniform density layers**
  - **Range of core densities for Vesta**
  - **Range of crustal densities from HEDs for Vesta**
  - **Can't really assume anything for Ceres**



Key results of Finite-Element Modeling

Vesta (Fu et al., 2014)

- Vesta experienced <u>early efficient relaxation</u> due to early formation and heating from ^{26}Al
- Vesta cooled quickly and Rheasilvia and Veneneia basins formed then Vesta <u>was cool and not relaxing</u>
- Northern terrains represent fossil figure

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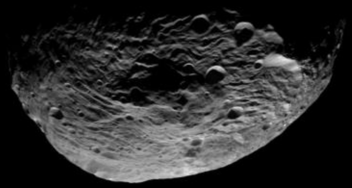
Ceres (Fu et al., submitted)

- Ceres crust is ≈ 1000 times stronger than water ice
- Ceres crust must be dominated by rock-like materials, water ice in the Ceres' crust < 30 vol%
- The rest is inferred to be combination of serpentine phyllosilicates, clathrates and/or salts to satisfy density and rheology constraints



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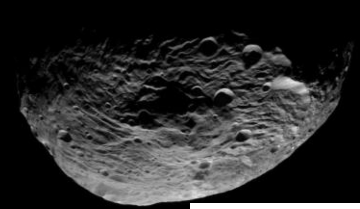
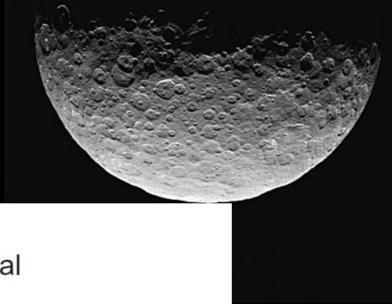
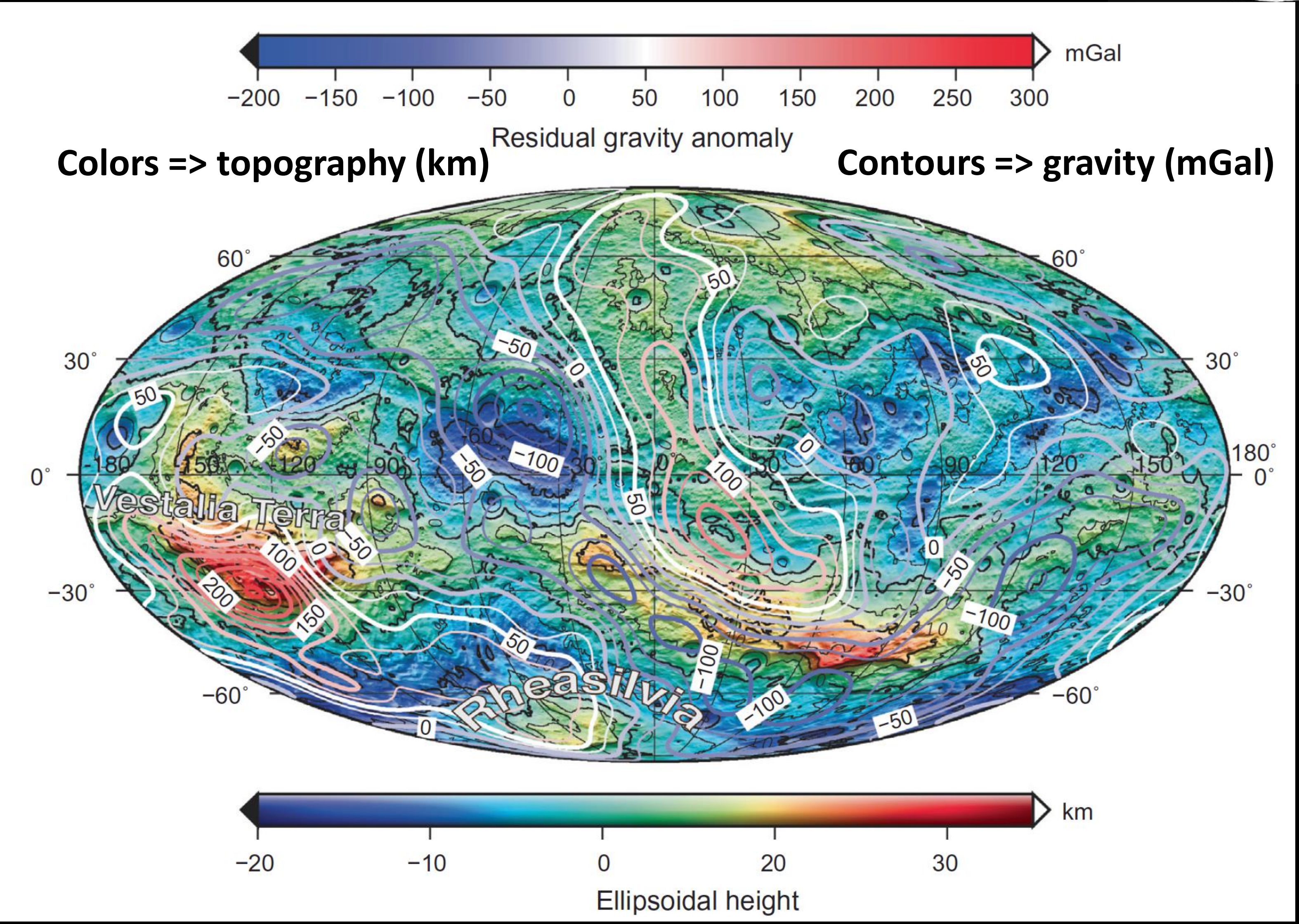


Vesta's Bouguer Anomaly



Colors => topography (km)

Contours => gravity (mGal)



Ermakov et al., 2014

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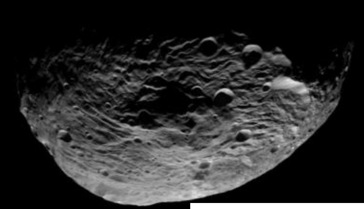

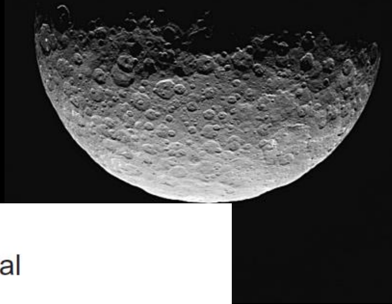

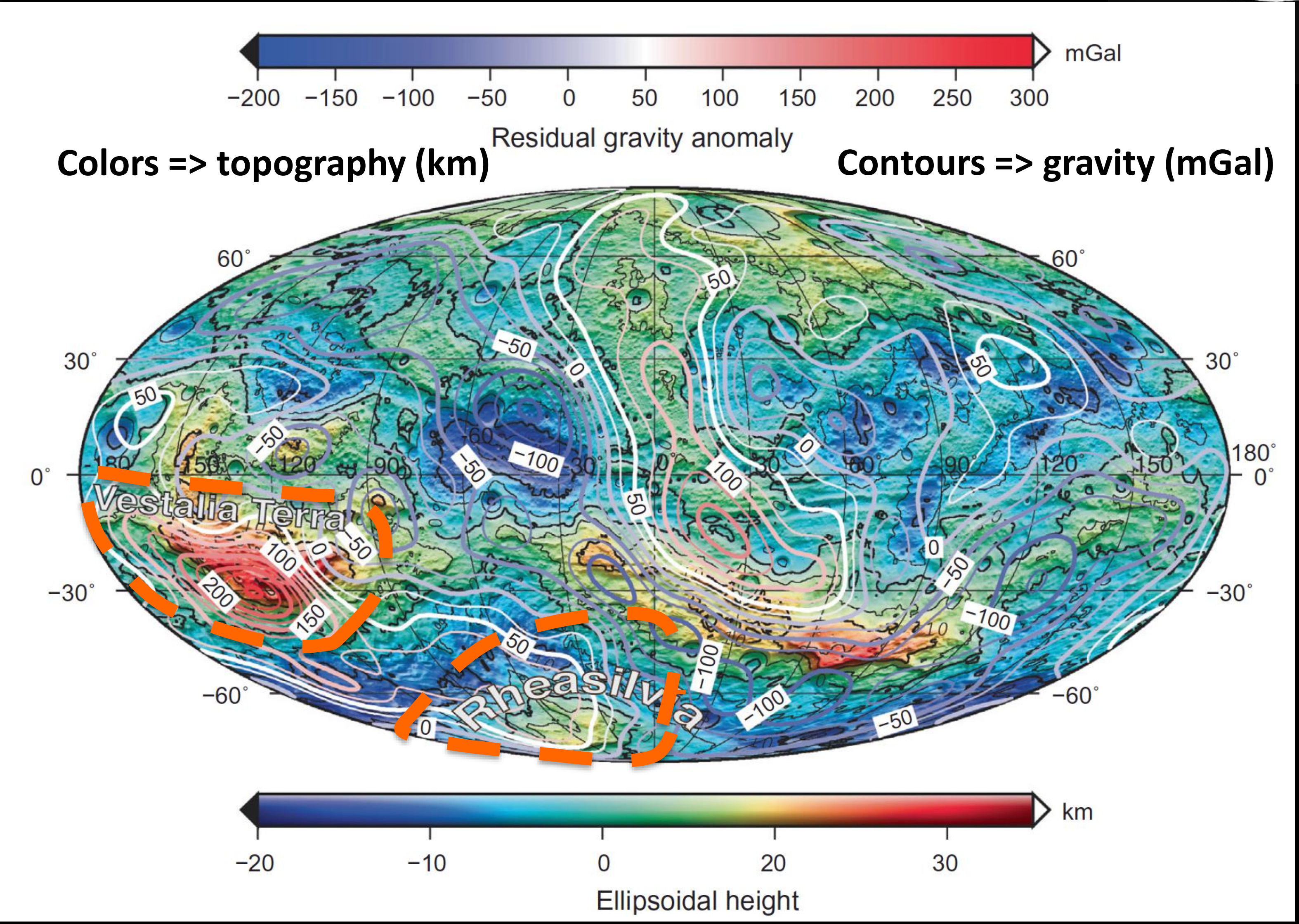

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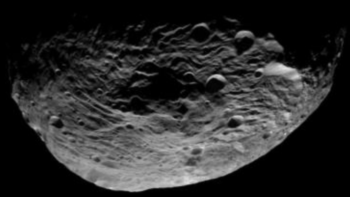

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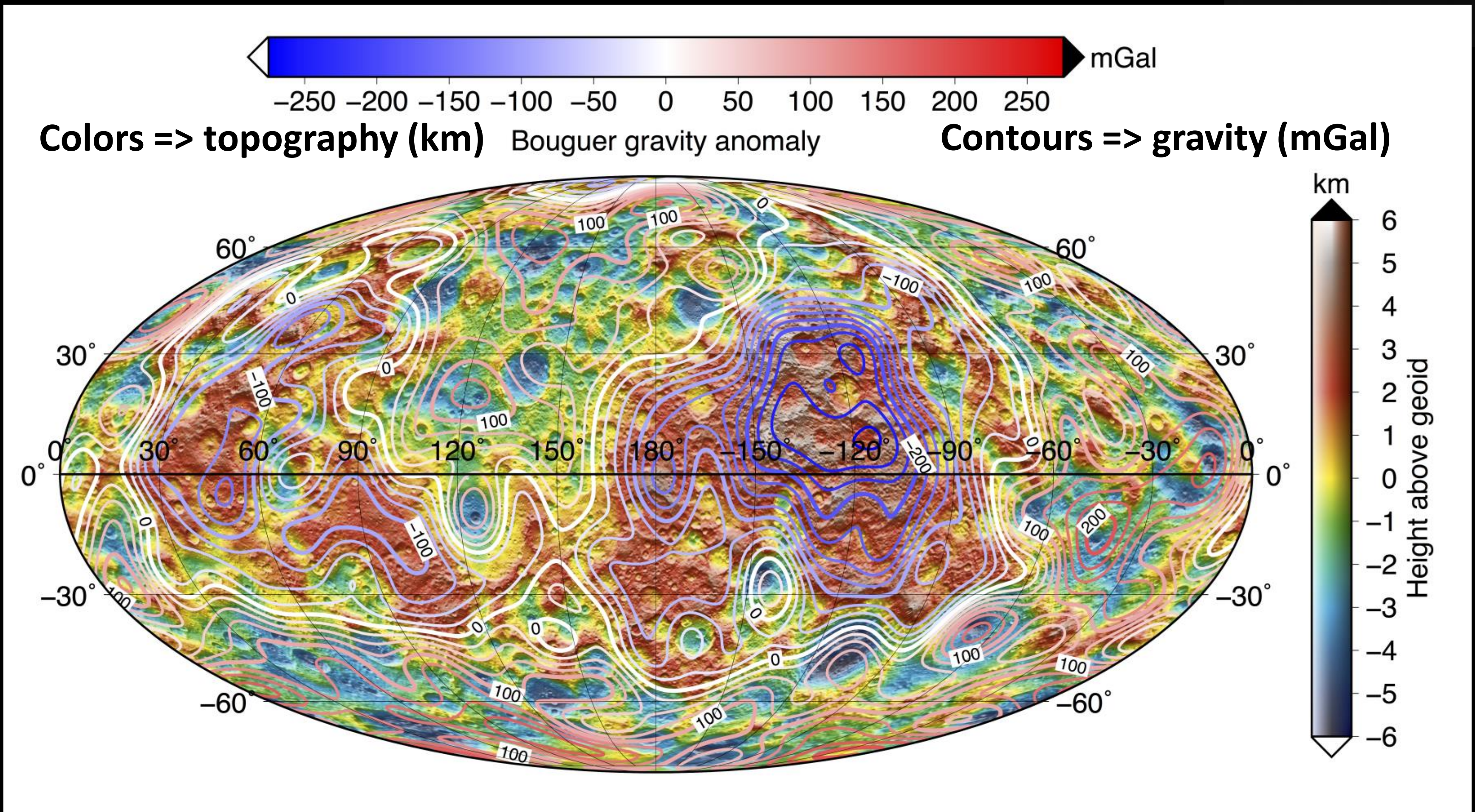
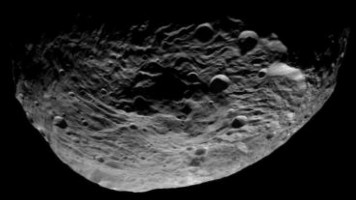


Ermakov et al., submitted to JGR



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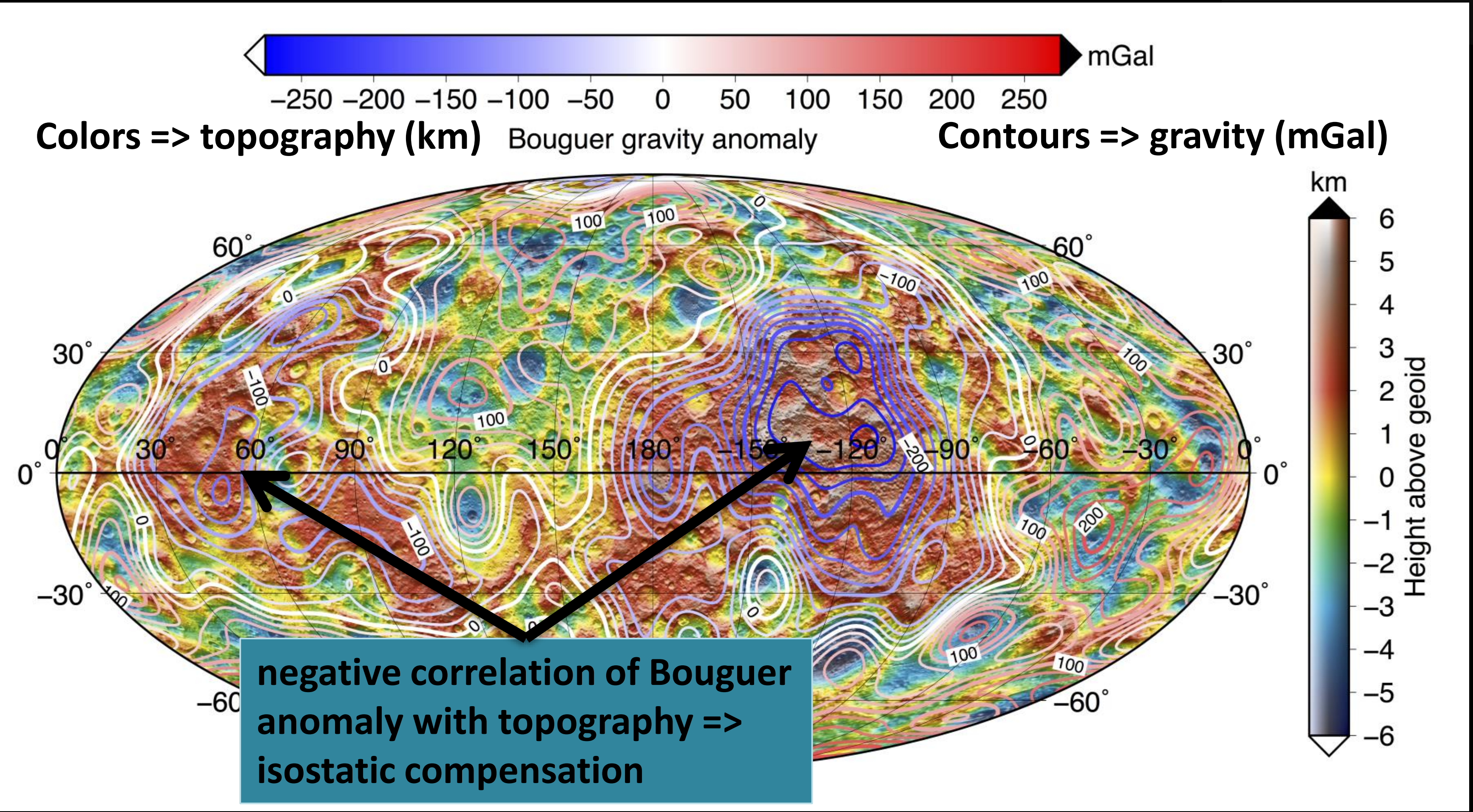

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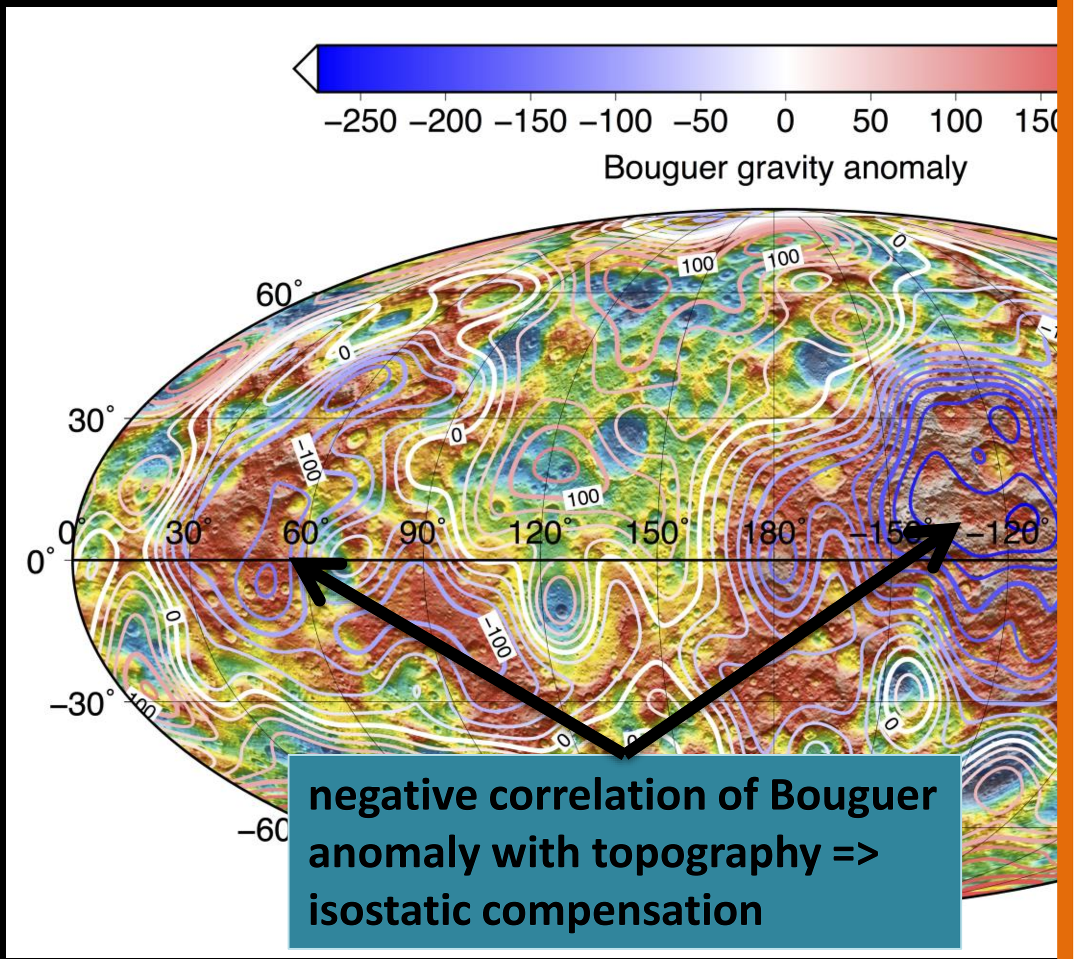

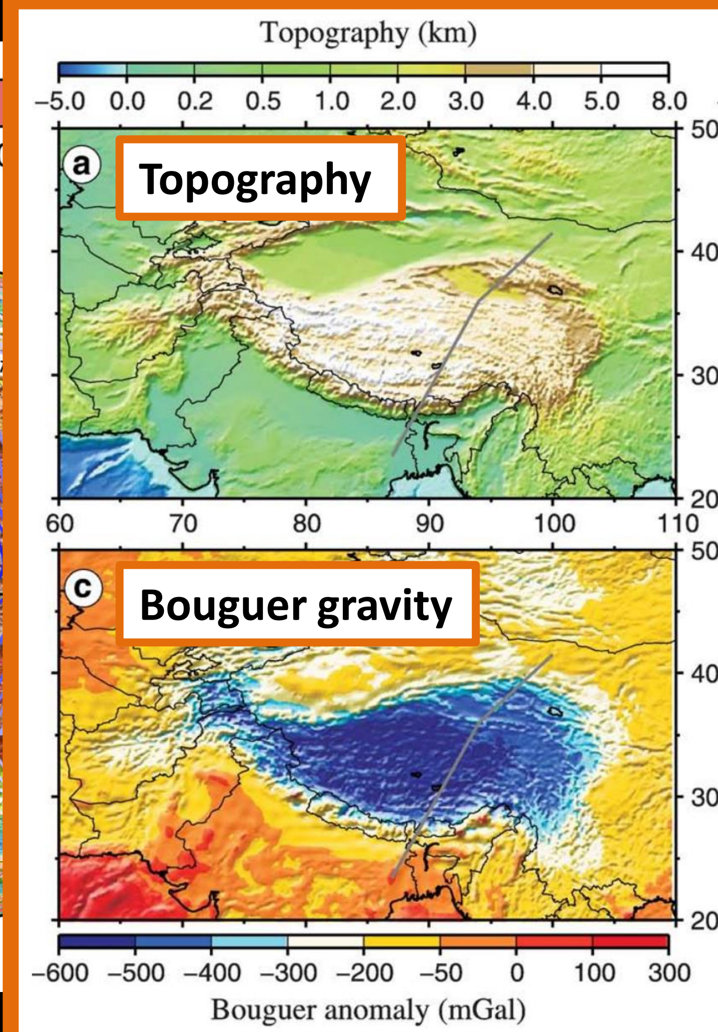

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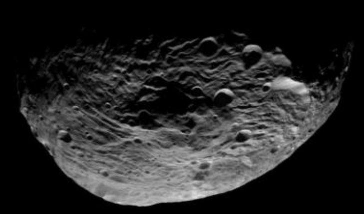
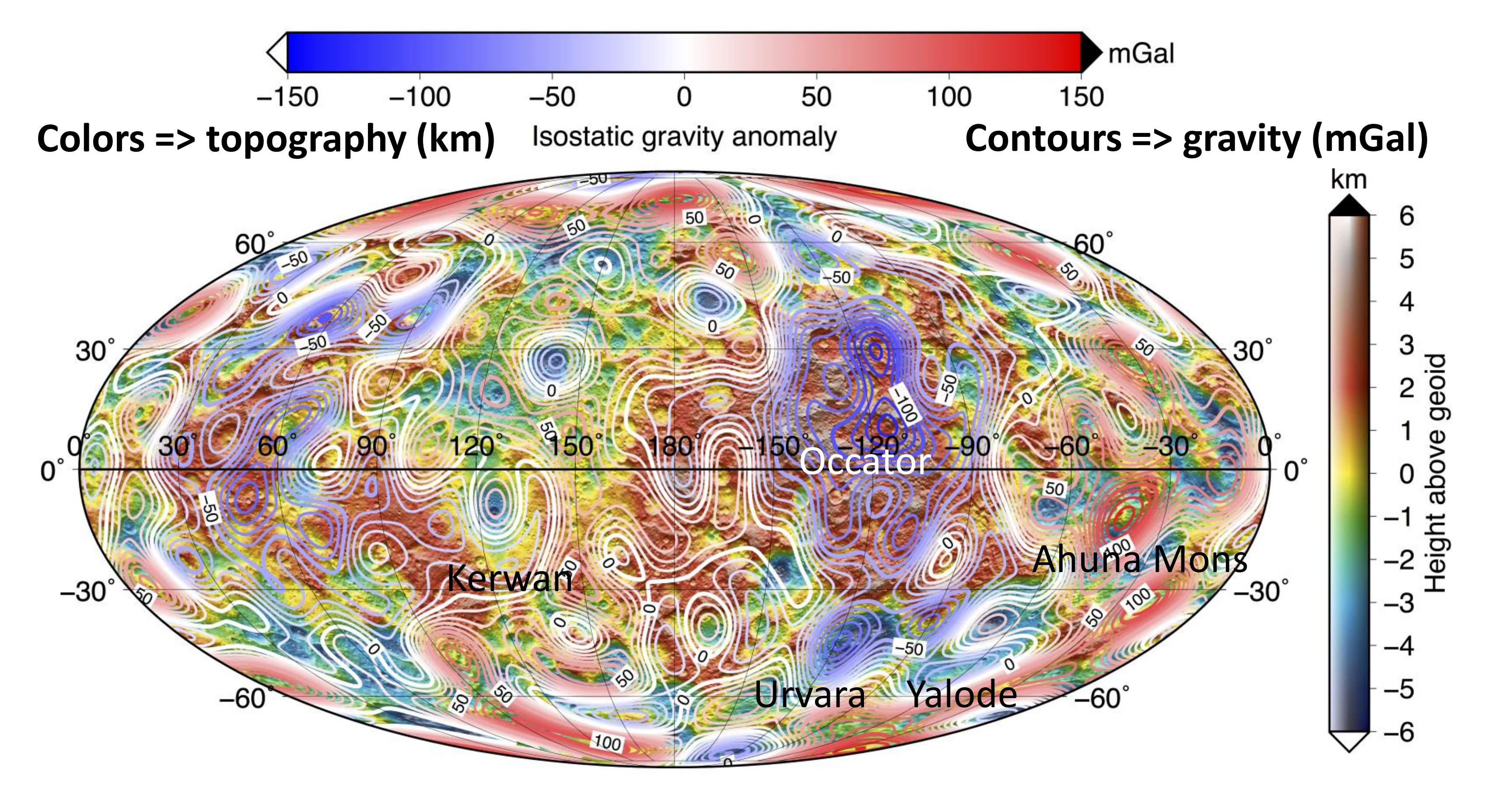


Ceres' Isostatic Anomaly



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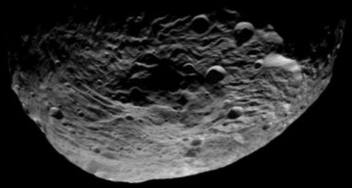

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Spectral comparisons

R_n - Correlation

$$R_n = \frac{S_n^{gt}}{\sqrt{S_n^{tt} S_n^{gg}}}$$

grav-topo cross-power

grav. power

topo. power

- R_n tells how well phases of gravity and topography match

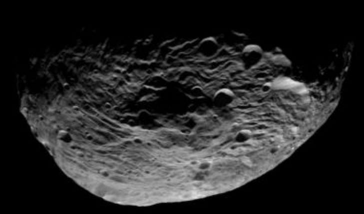
n – spherical harmonic degree ~ 1/wavelength

Z_n - gravity-topography admittance

$$Z_n = \frac{S_n^{gt}}{S_n^{tt}}$$

- Z_n is a transfer function between gravity and topography
- Say Z_n = 50 mGal/km:

  A topography wave with a height of 1 km gives a gravity wave of 50 mGal



Spectral comparisons

Z_n - gravity-topography admittance

$$Z_n = \frac{S_{gt}}{S_{tt}}$$

- **Uniform density**

$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}$$

- **Two-layer model**

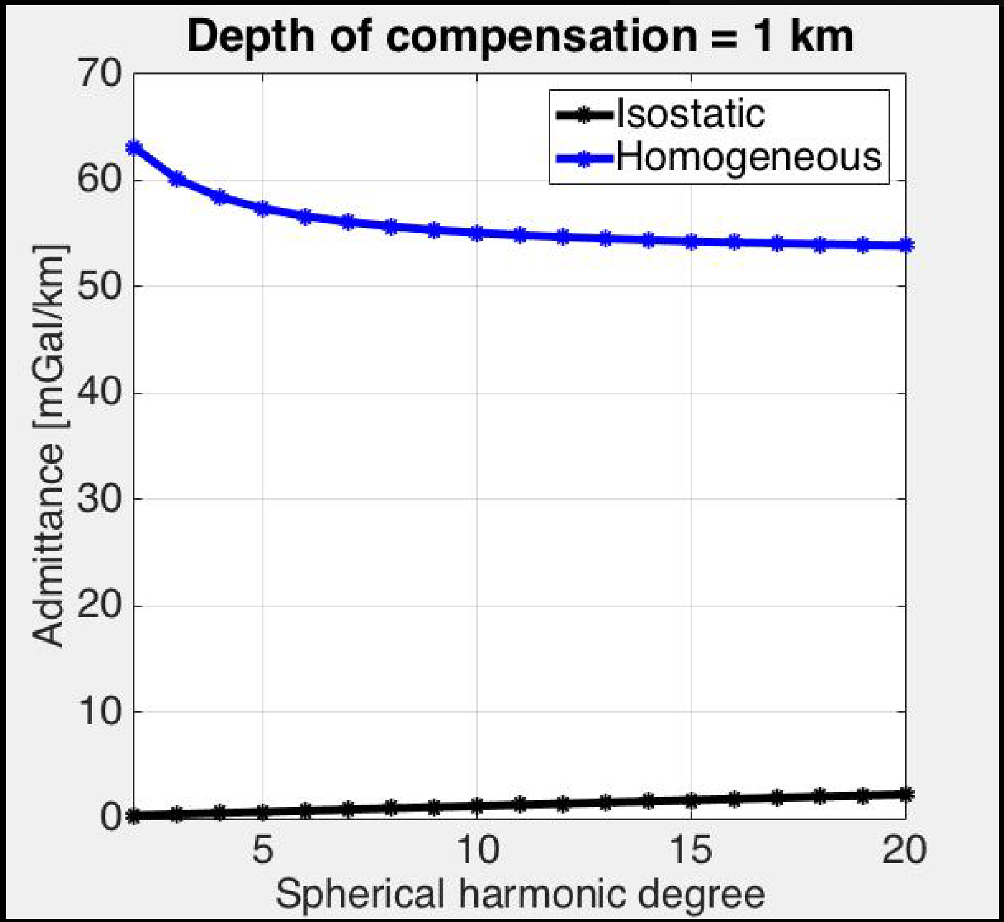
$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{\rho_{crust}}{\rho_{mean}}$$

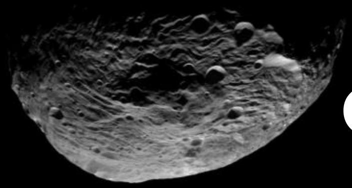
- **Isostatic two-layer model**

$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{\rho_{crust}}{\rho_{mean}}\left[1-\left(1-\frac{D_{comp}}{R}\right)^n\right]$$

<- Isostatic factor reducing admittance

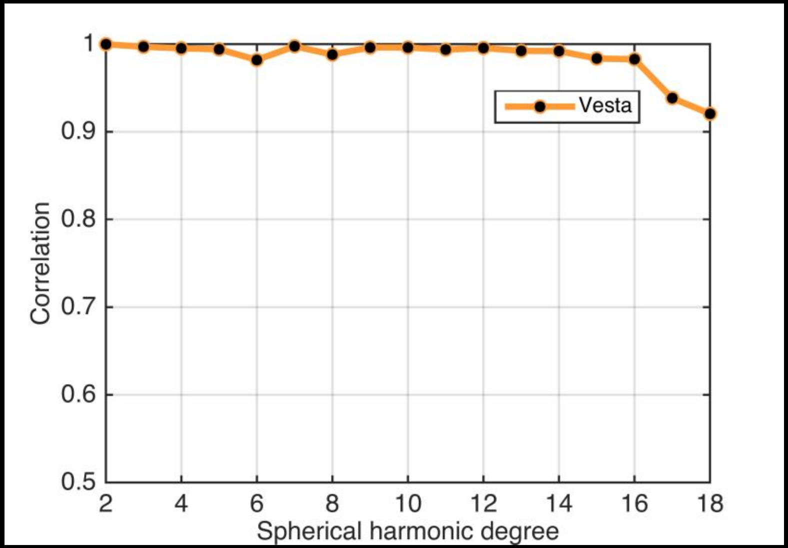
- **Example of admittance spectrum for Ceres-like parameters**





Correlation (*R*)

- ***R* is expected to be unity if there is no lateral density variations**



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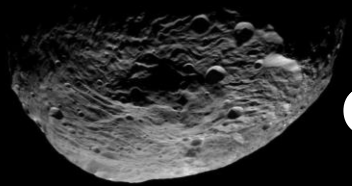
Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.



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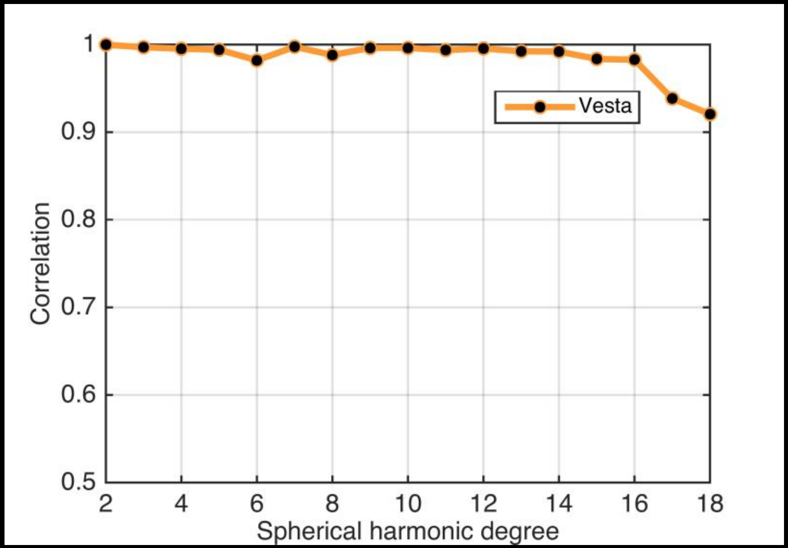

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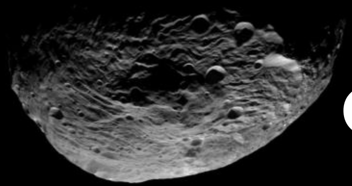

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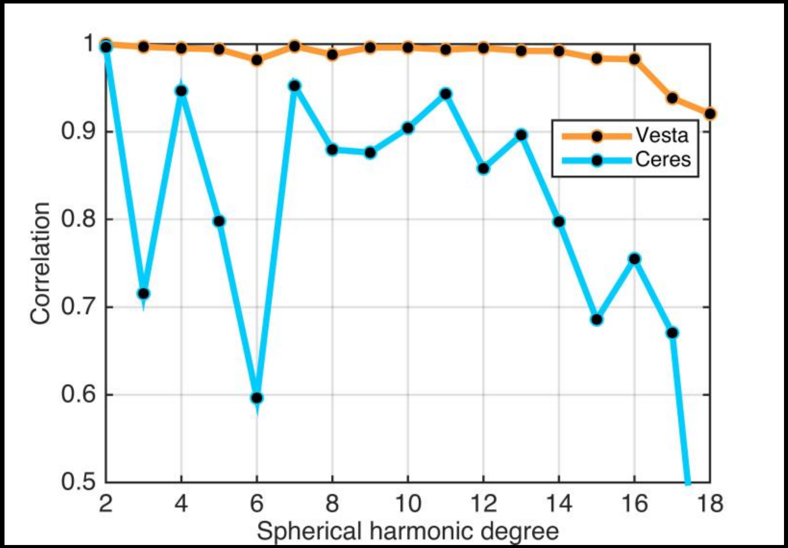

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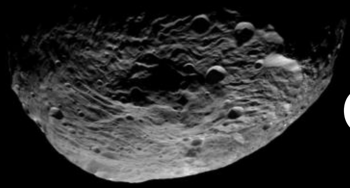

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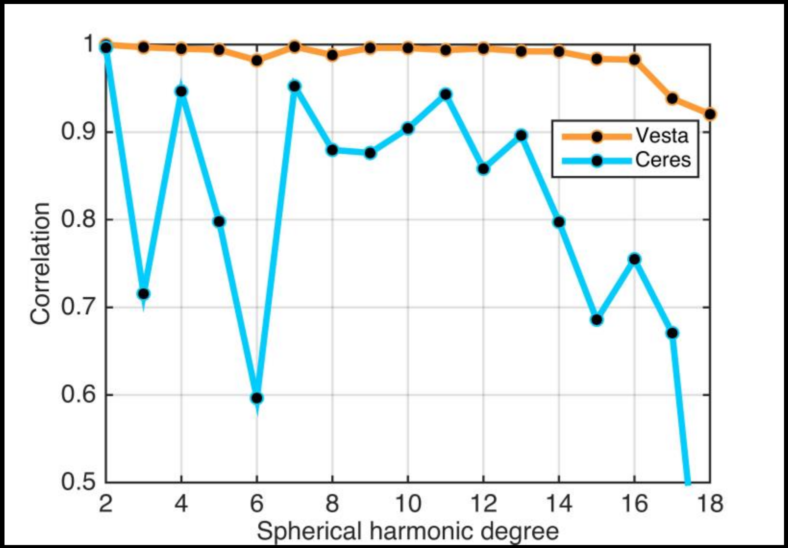

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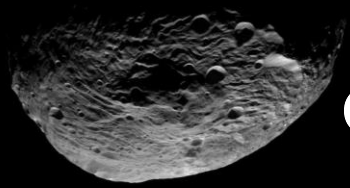
Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.



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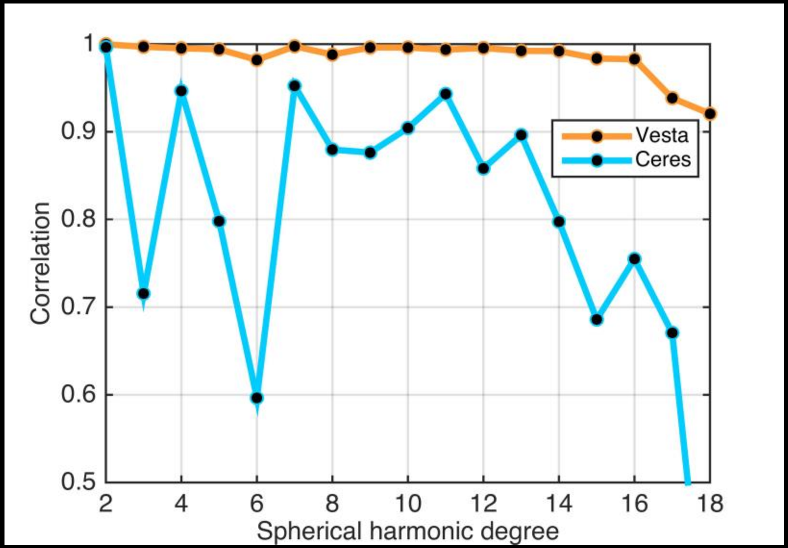

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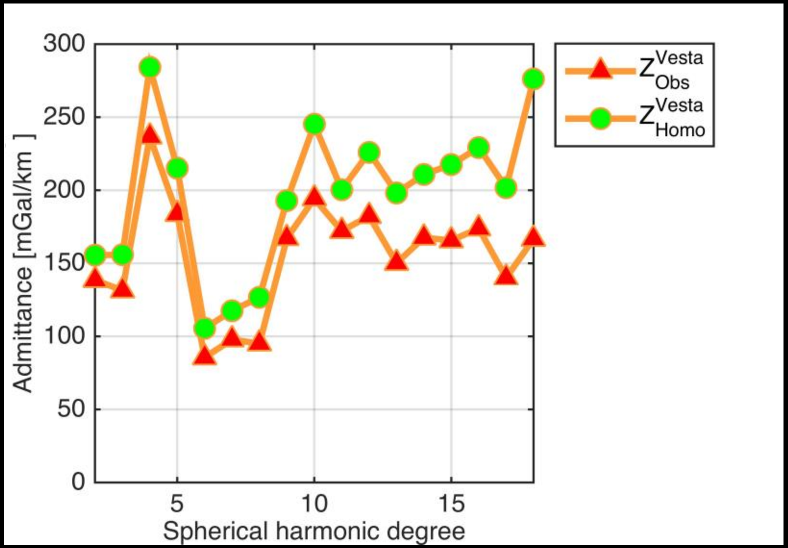

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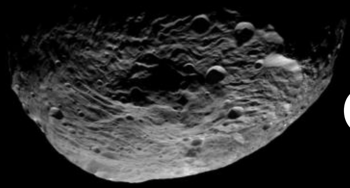

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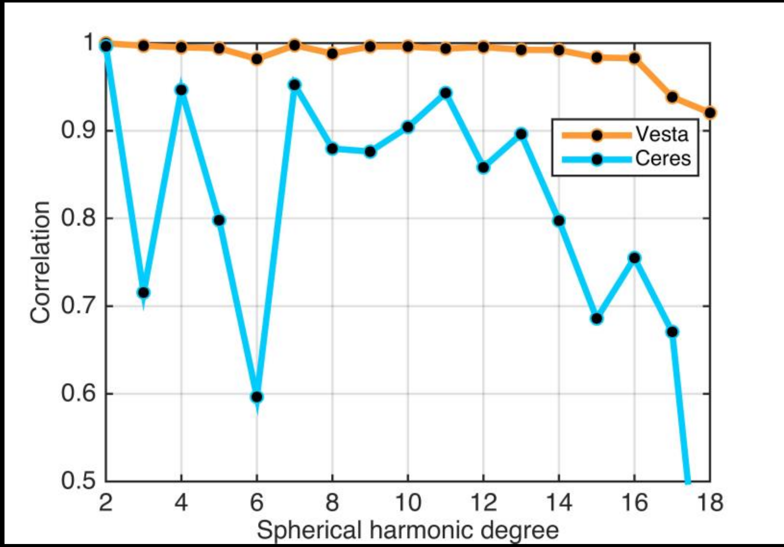

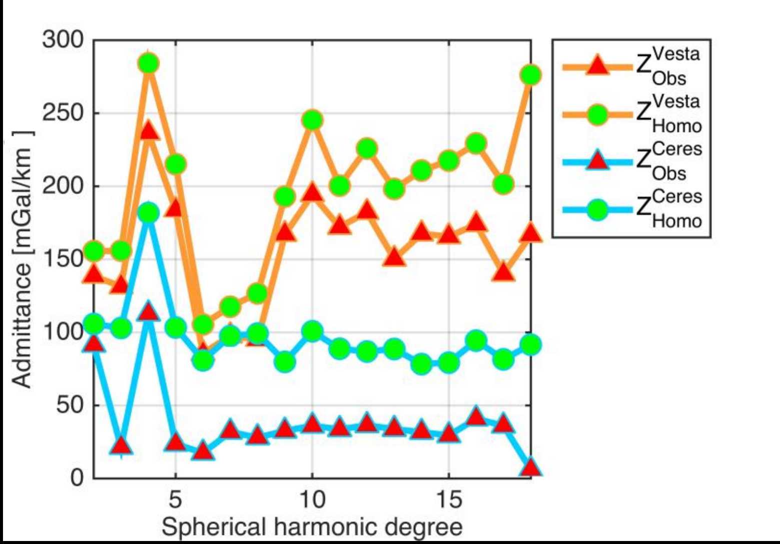

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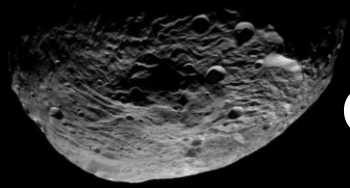

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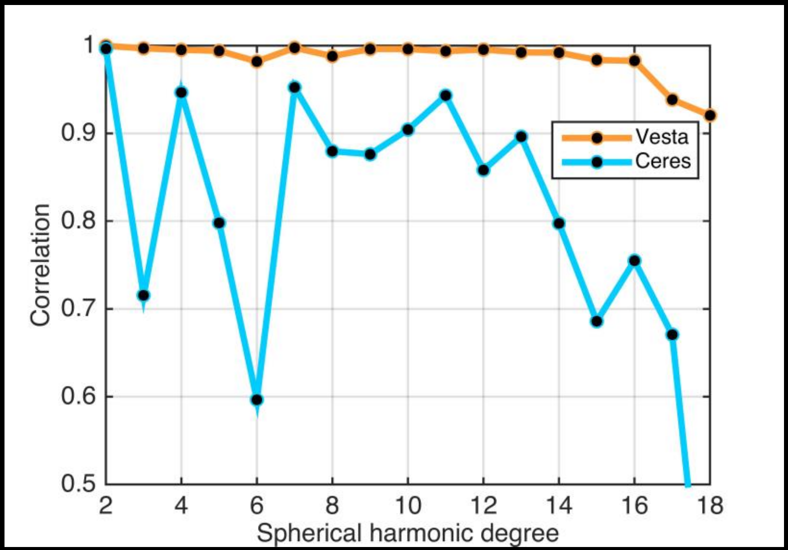
- $Z_{observed}/Z_{homo}$ tells about the nature of topography compensation



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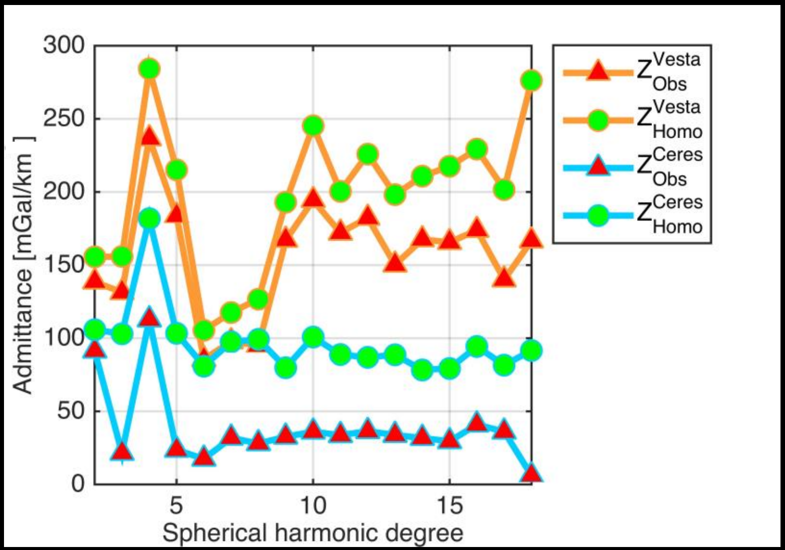

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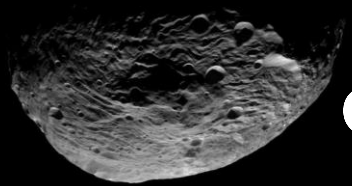

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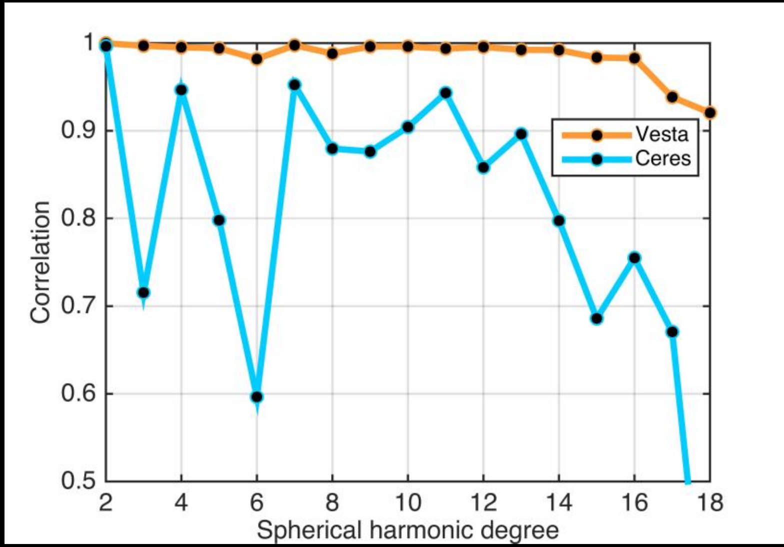

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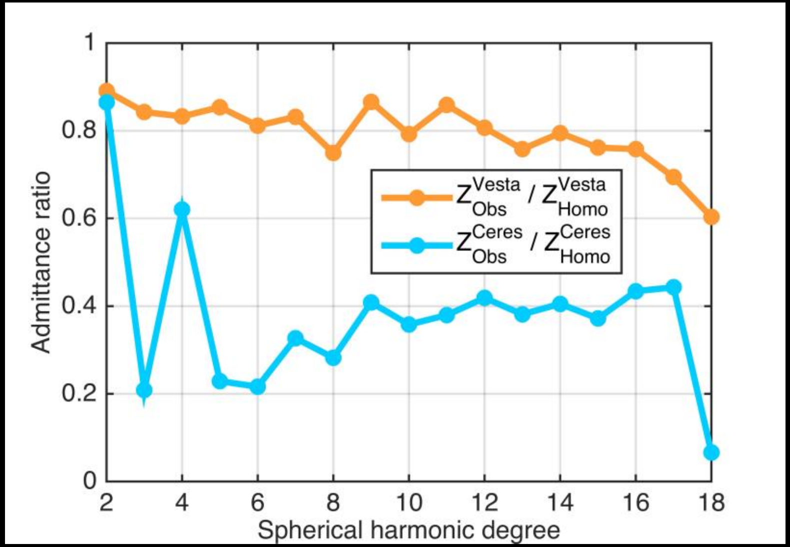
$Z_{observed}/Z_{homo}$



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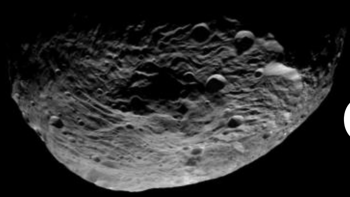

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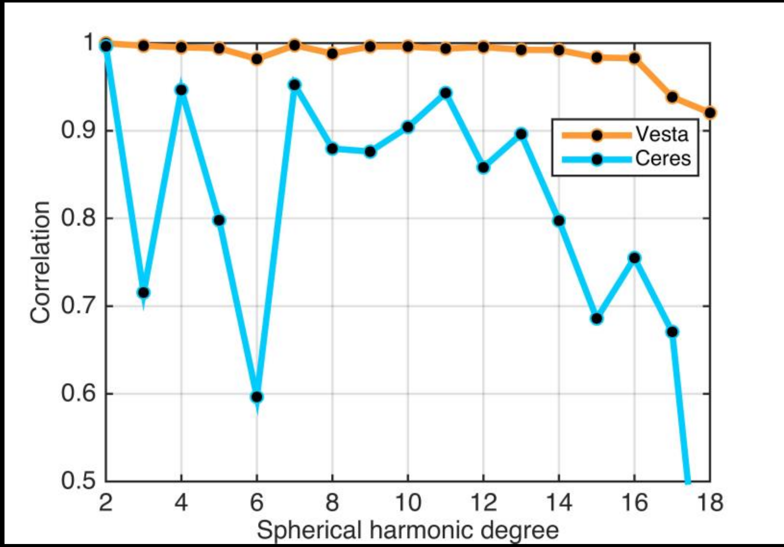
- **$Z_{observed}$ should be equal to Z_{homo} for a homogeneous body**
- **$Z_{observed}/Z_{homo}$ tells about the nature of topography compensation**
- **$Z_{observed}/Z_{homo}$ consistent with <u>uncompensated</u> topography for Vesta**



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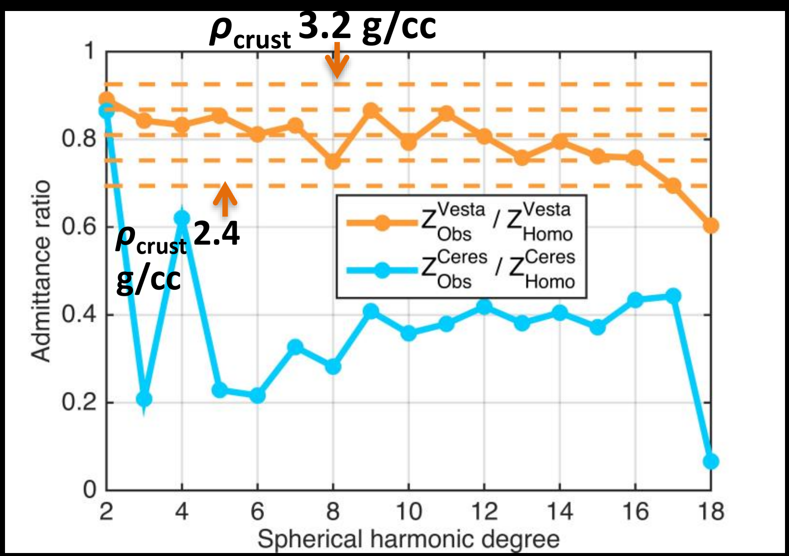
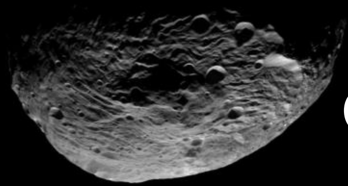


Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.

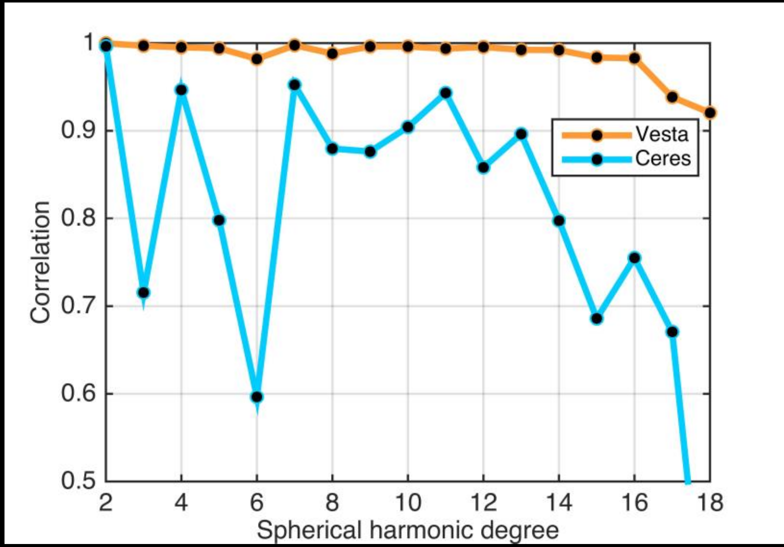


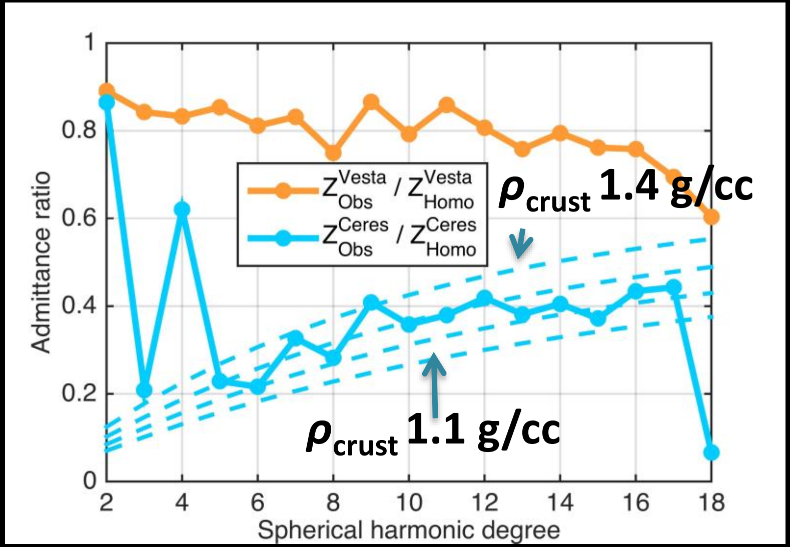
Correlation (R)

- R is expected to be unity if there is no lateral density variations
- R_{vesta} are close to unity implying small lateral density variations
- R_{ceres} are significantly lower implying inhomogeneities in the crust

Admittance (Z)

- $Z_{observed}$ should be equal to Z_{homo} for a homogeneous body
- $Z_{observed}/Z_{homo}$ tells about the nature of topography compensation
- $Z_{observed}/Z_{homo}$ consistent with <u>compensated</u> topography for Ceres





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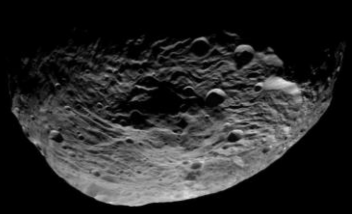
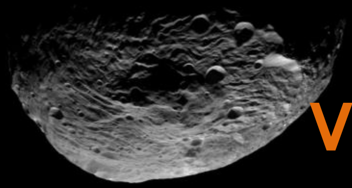
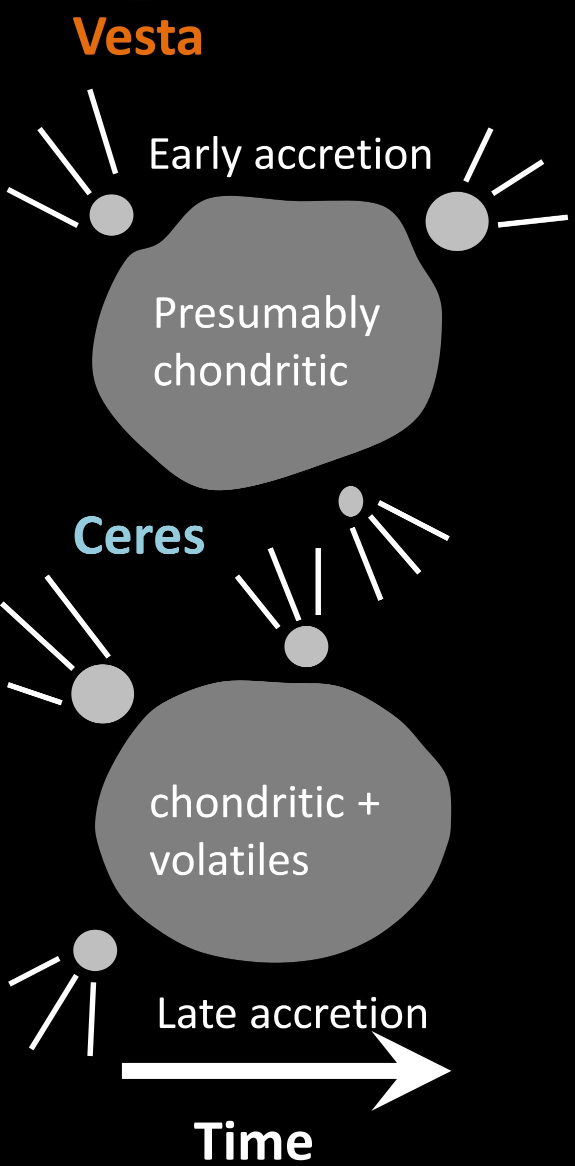


Outline

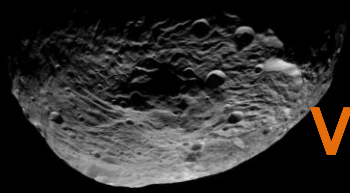
- State of internal structure modeling before Dawn
- Data available from Dawn
- Look at gravity and topography spatially
- Look at gravity and topography spectrally
- **Compare evolutions of Vesta and Ceres**
- Summary of findings



Vesta and Ceres comparative evolution



Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.



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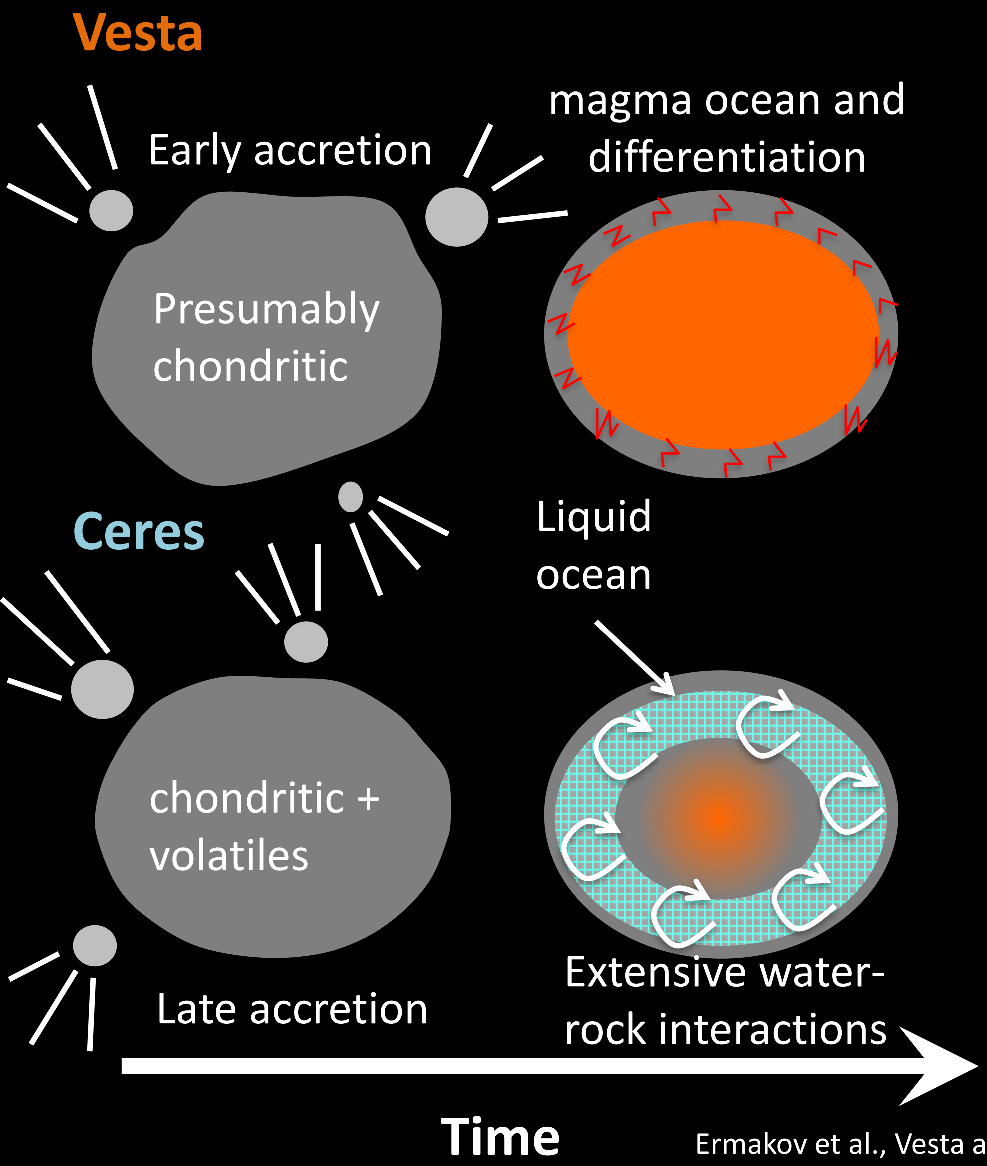

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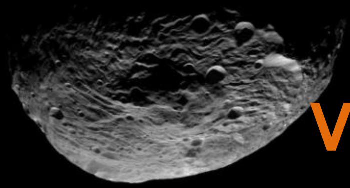
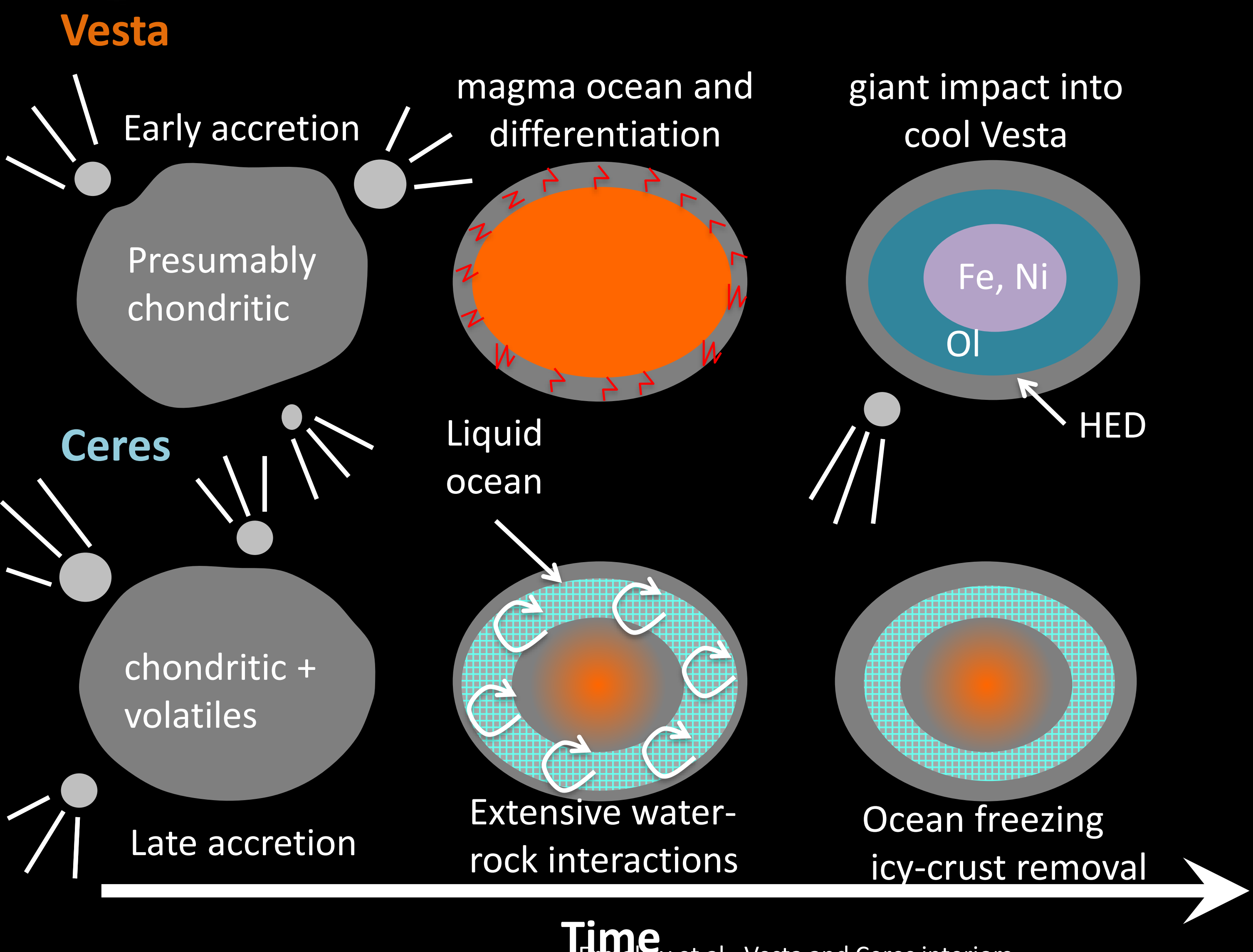
Vesta and Ceres comparative evolution





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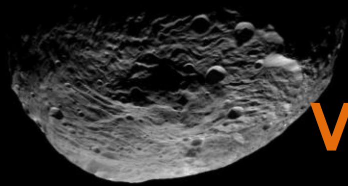

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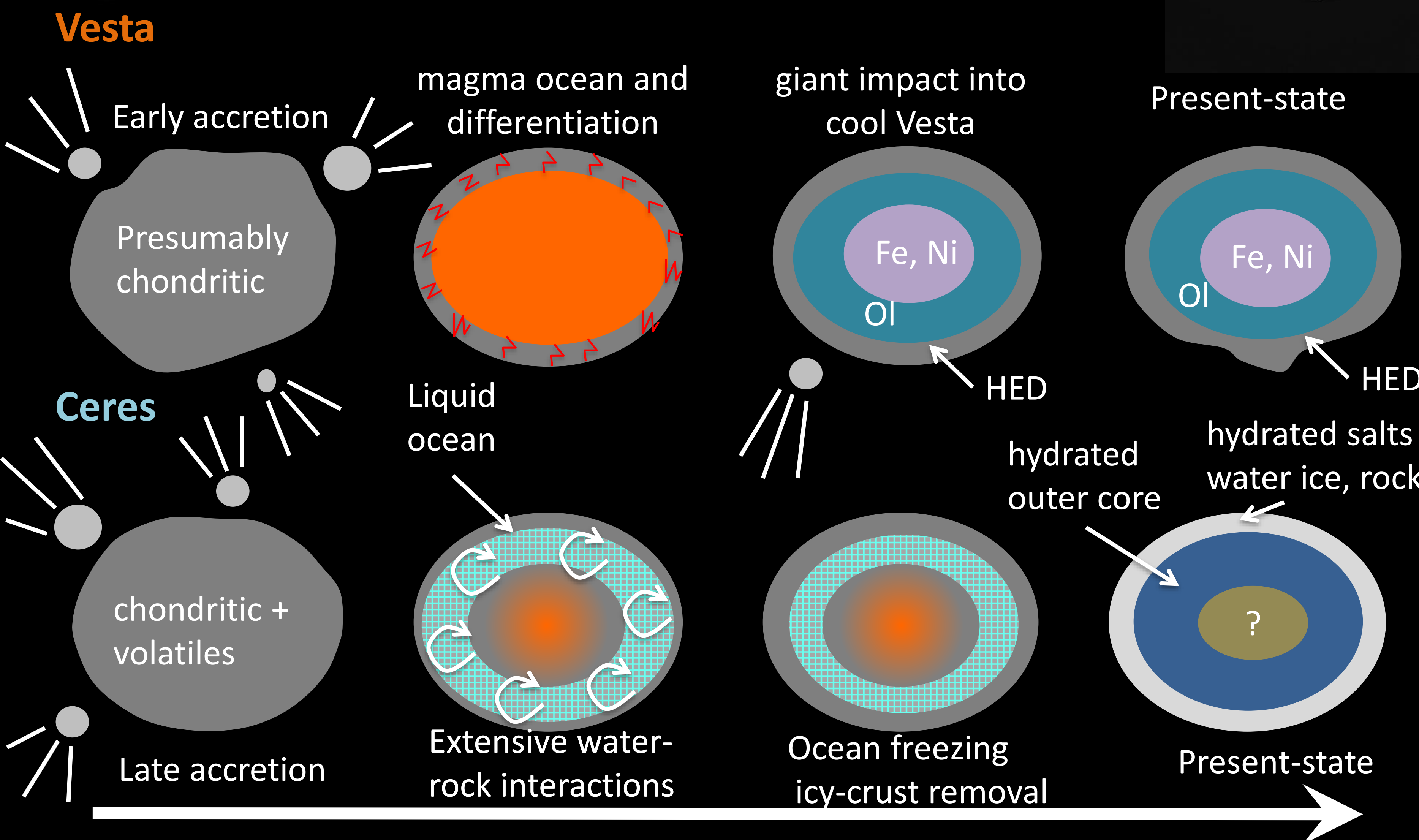
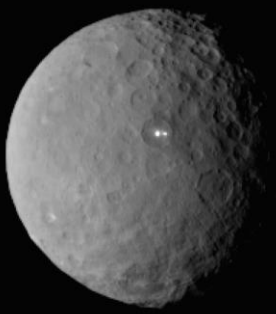


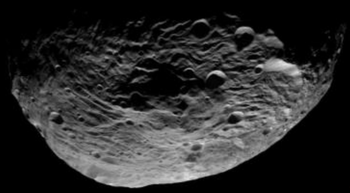
Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.

Summary

- Formed early (< 5 My after CAI)
- Once hot and hydrostatic, Vesta is no longer either
- Differentiated interior
- Most of topography acquired when Vesta was already cool => uncompensated topography
- Combination of gravity/topography data with meteoritic geochemistry data provides constraints on the internal structure

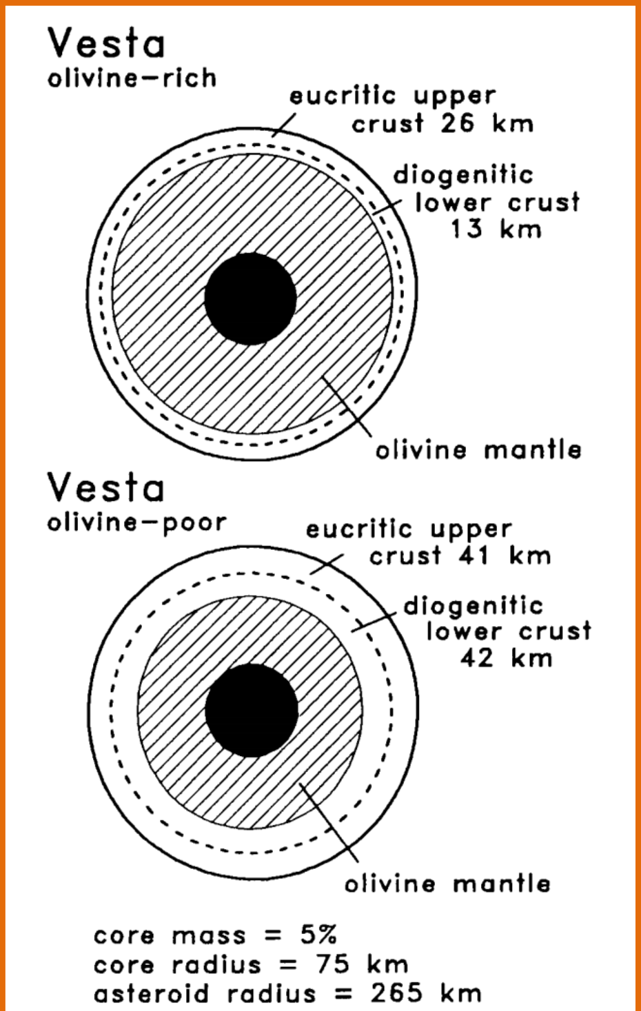


- Cooler history
  - either late formation (> 5 My after CAI)
  - or heat transfer due to hydrothermal circulation
- Partially differentiated interior
- Experienced viscous relaxation
- Much lower surface viscosities (compared to Vesta) allowed compensated topography
- Ceres' crust is light (based on admittance analysis) and strong (based on FE relaxation modeling)
- Not much water ice in Ceres crust (<30 vol%) now



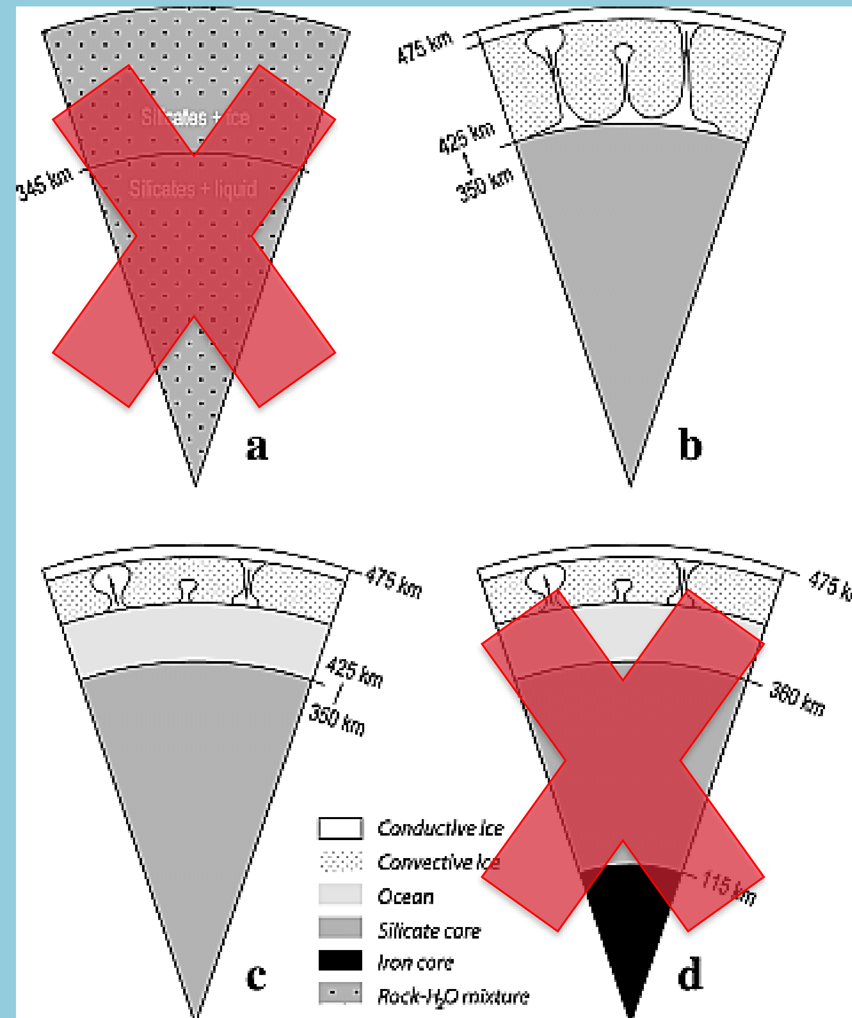
So what do we know now?

Vesta

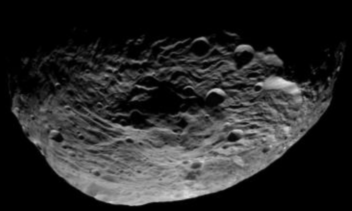


Ruzicka et al., 1997

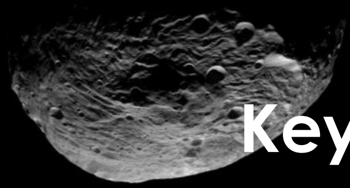
Ceres



McCord and Sotin, 2005

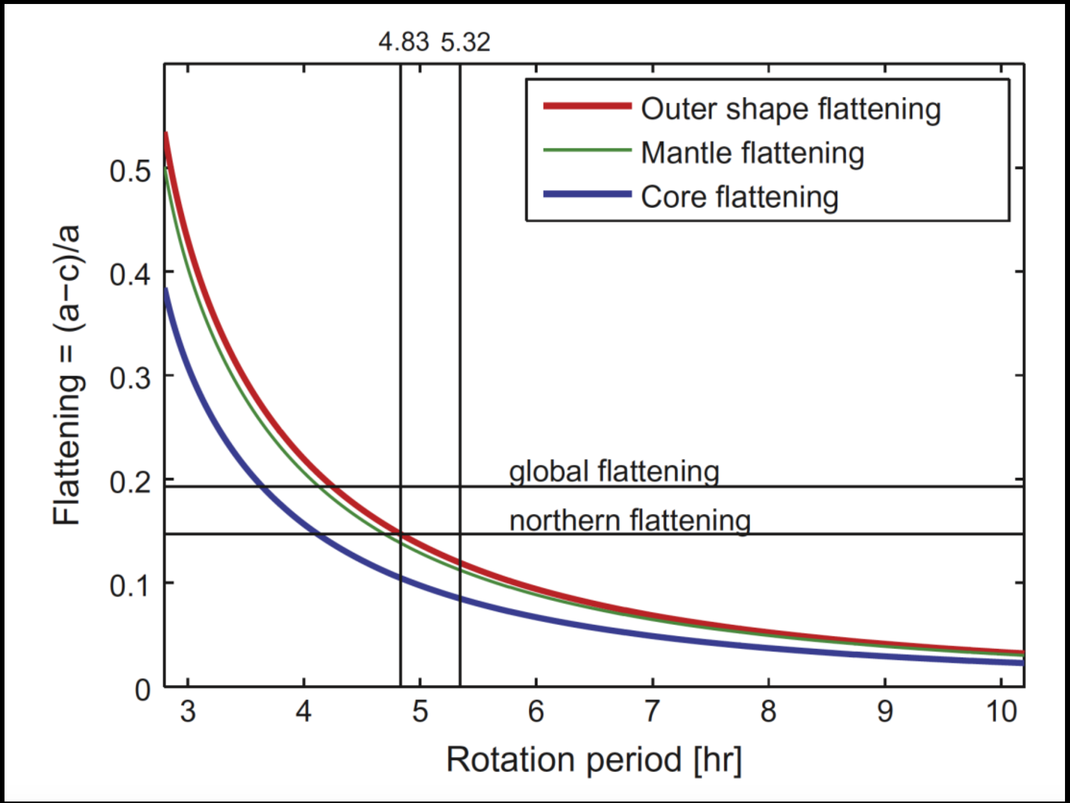


Backup slides



Key results from thermal and impact modeling

- Vesta was likely close to hydrostatic equilibrium in its early history
- Major impact occurred when Vesta was effectively non-relaxing
- The areas >50° away from major impacts were not significantly deformed
- Crater counting reveals that the northern Vesta terrains are old (>3Gy)
- Northern terrains likely represent the pre-impact shape of Vesta.

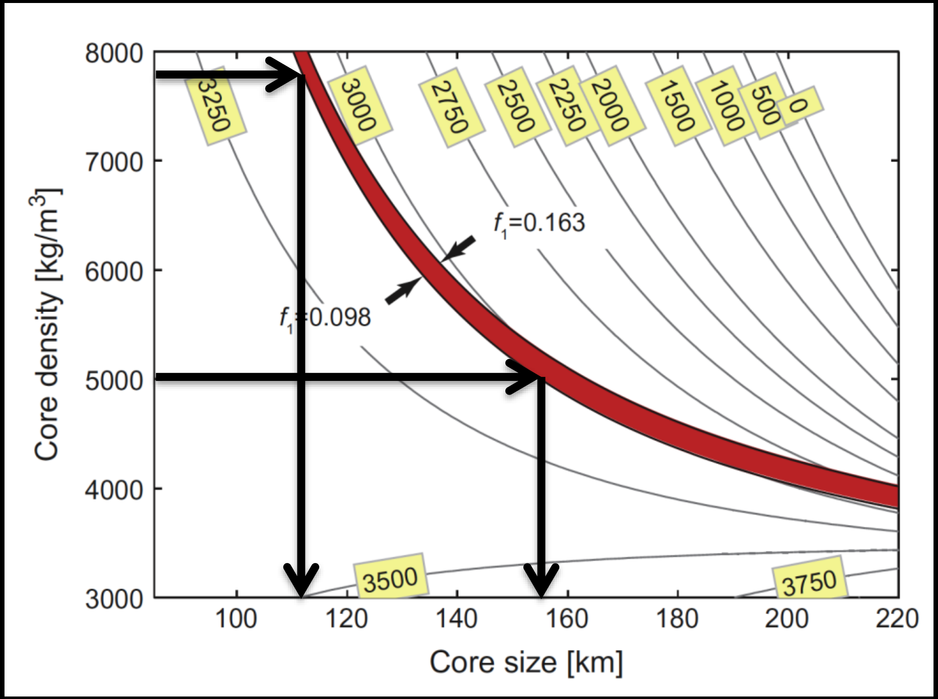


Ermakov et al., 2014

Interior structure modeling

- Vesta is not presently in hydrostatic equilibrium
- No unique solution **only** from gravity/topography, need an extra constraint
- Geochemically motivated 3-layer interior structure (Ruzicka et al., 1997)
- Densities constrained by the Howardite-Eucrite-Diogenite (HED) meteorites

Contours are mantle density [kg/m^3]

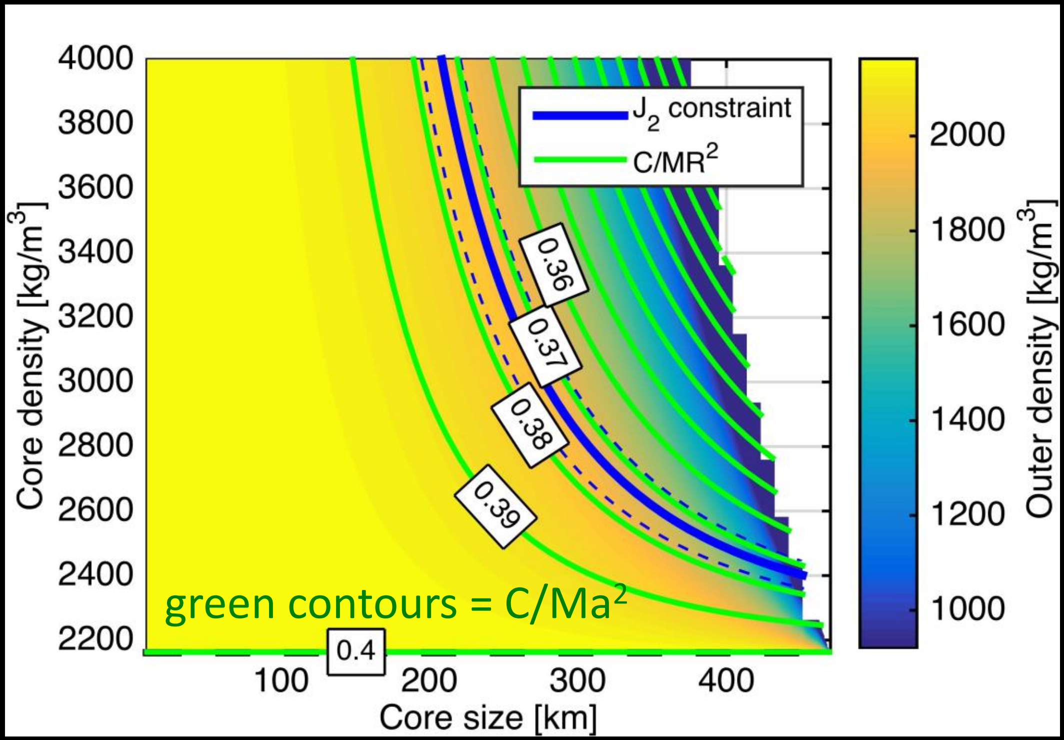


Core radius of 110 to 155 km

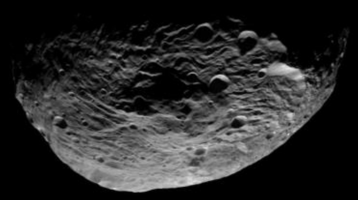
Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.

Two-layer model

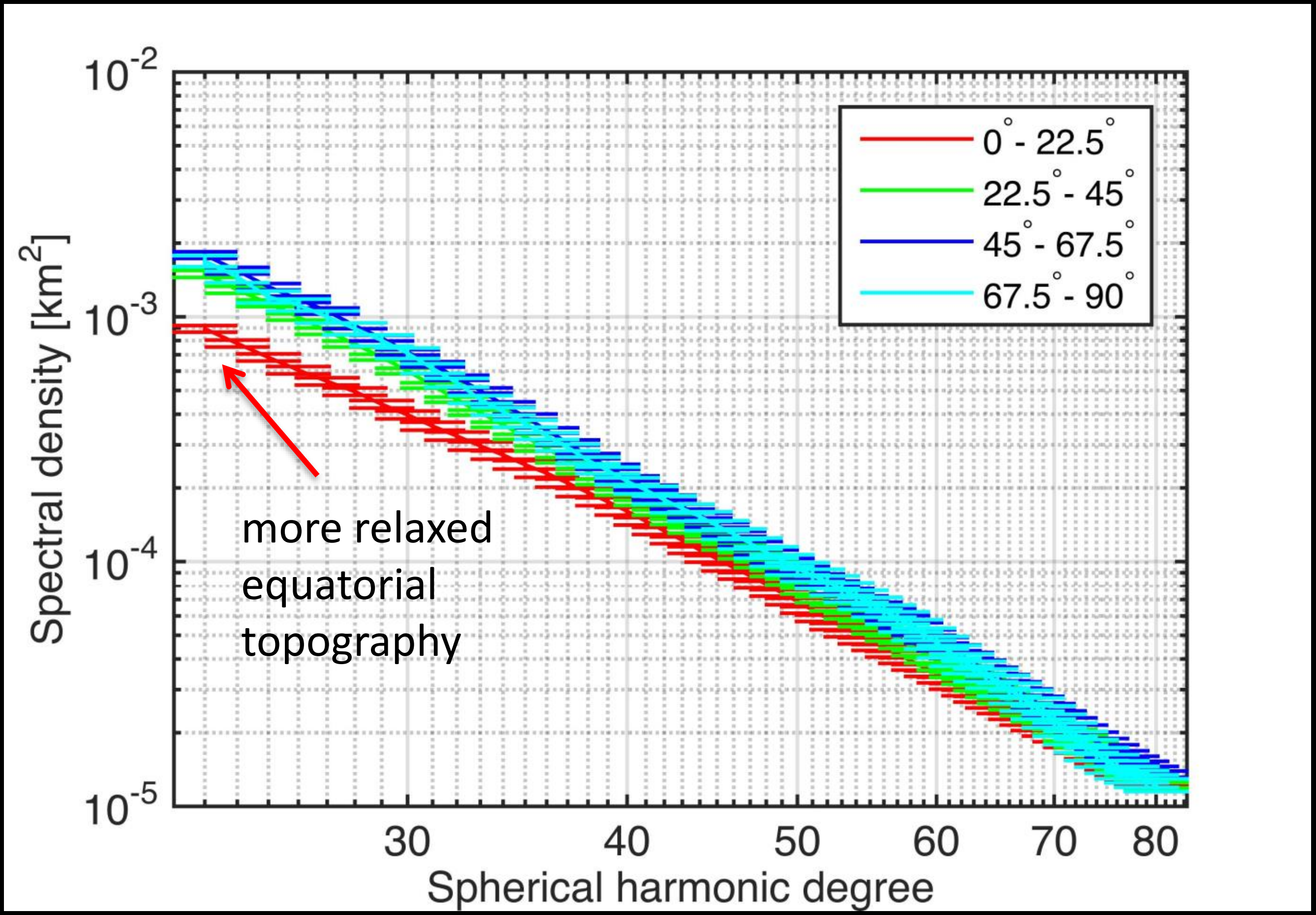
- **Simplest model to interpret the gravity-topography data**
- **Only 5 parameters: two densities, two radii and rotation rate**
- **Yields $C/Ma^2 = 0.373$ $C/M(R_{vol})^2 = 0.392$**



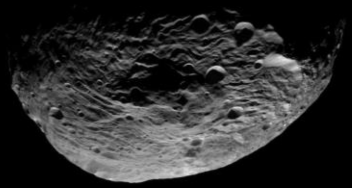
Using Tricarico 2014 for computing hydrostatic equilibrium



Latitude dependence of relaxation

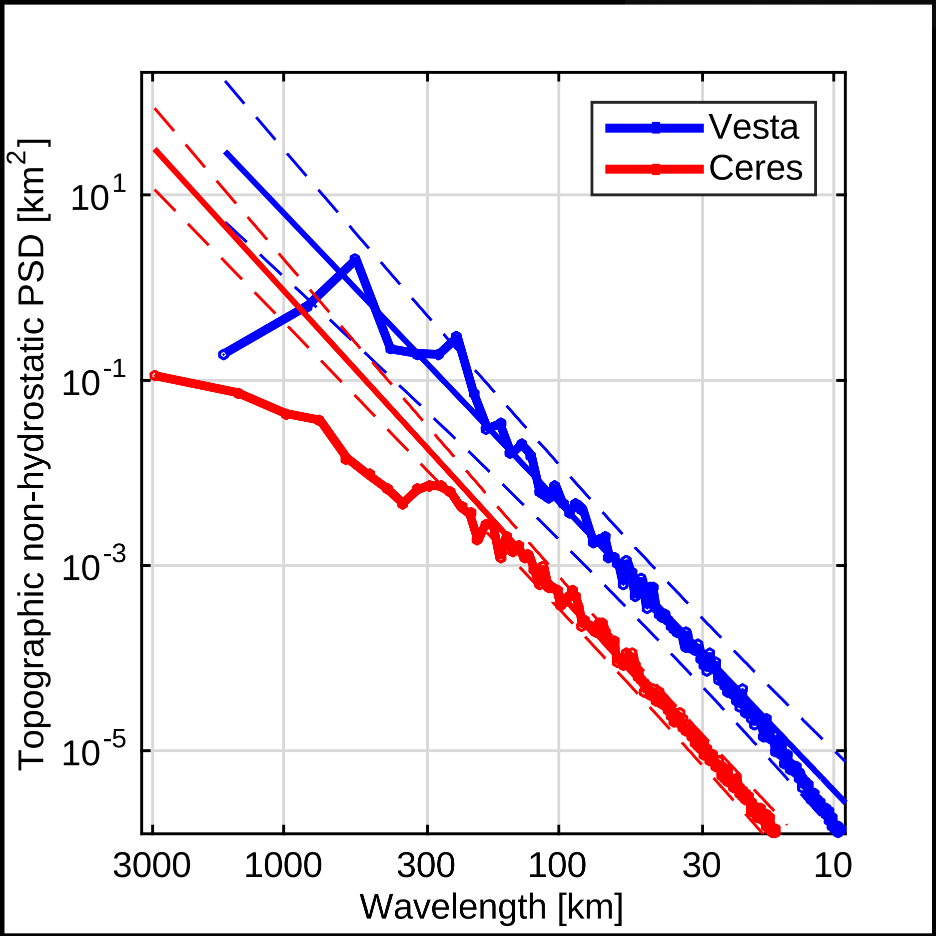


Ermakov et al., in prep

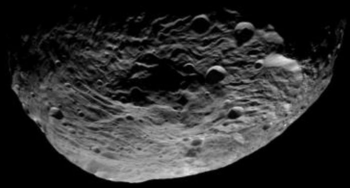


Evidence for viscous relaxation

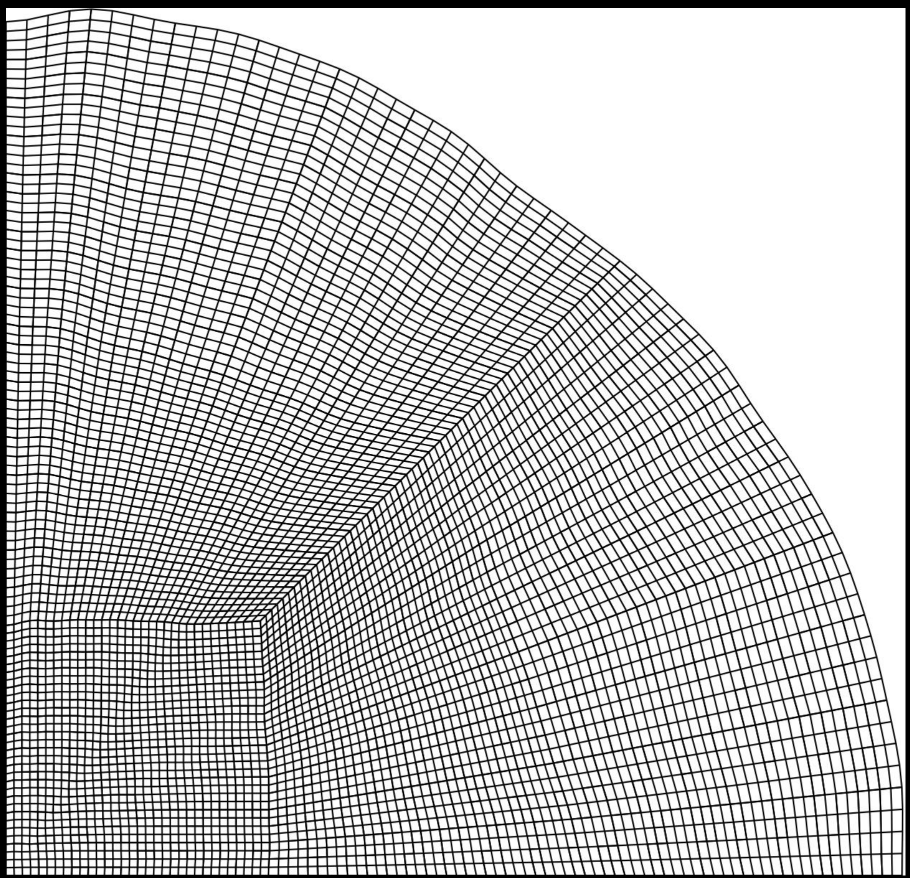
- **More general approach: study topography power spectrum**
- **Power spectra for Vesta closely fits with the power law to the lowest degrees (λ < 750 km)**
- **Ceres power spectrum deviates from the power law at λ > 270 km**



Ermakov et al,. in prep



Finite element model



Fu et al., 2014; Fu et al, submitted to EPSL

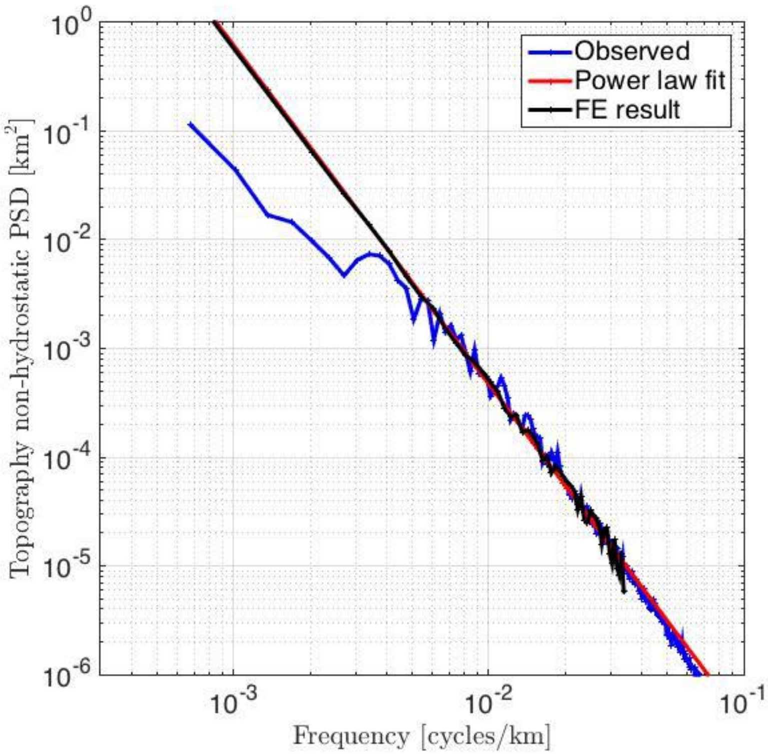
- **Assume a density and rheology structure**
- **Solve Stokes equation for an incompressible flow using deal.ii library**

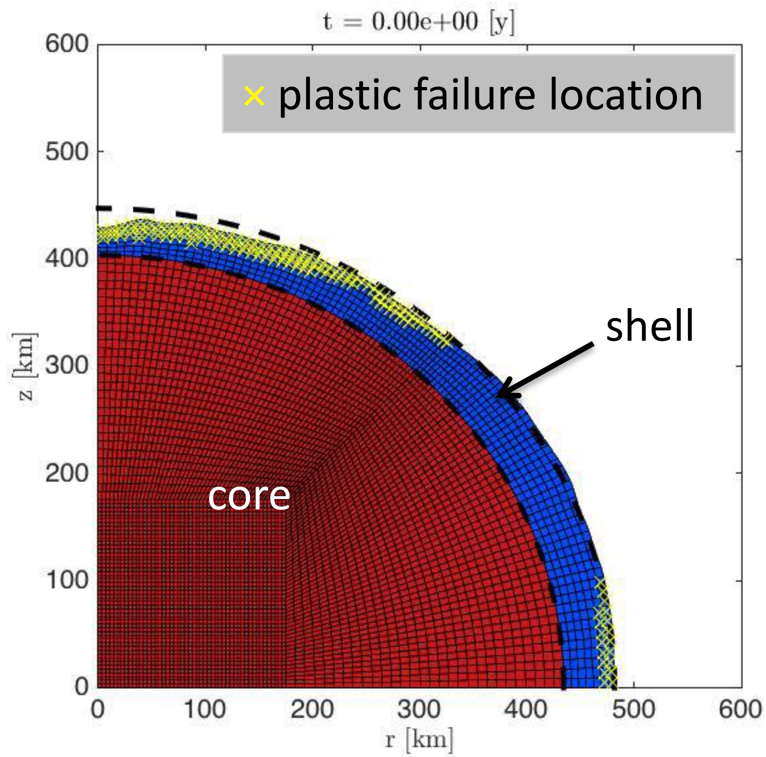
$$\partial_i(2\eta\dot{\varepsilon}_{ij}) - \partial_i p = -g_i\rho$$

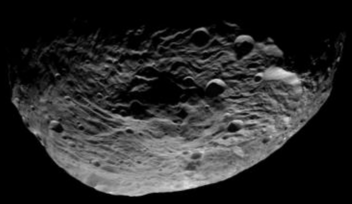
$$\P_i u_i = 0$$

- **Compute the evolution of the outer surface power spectrum**

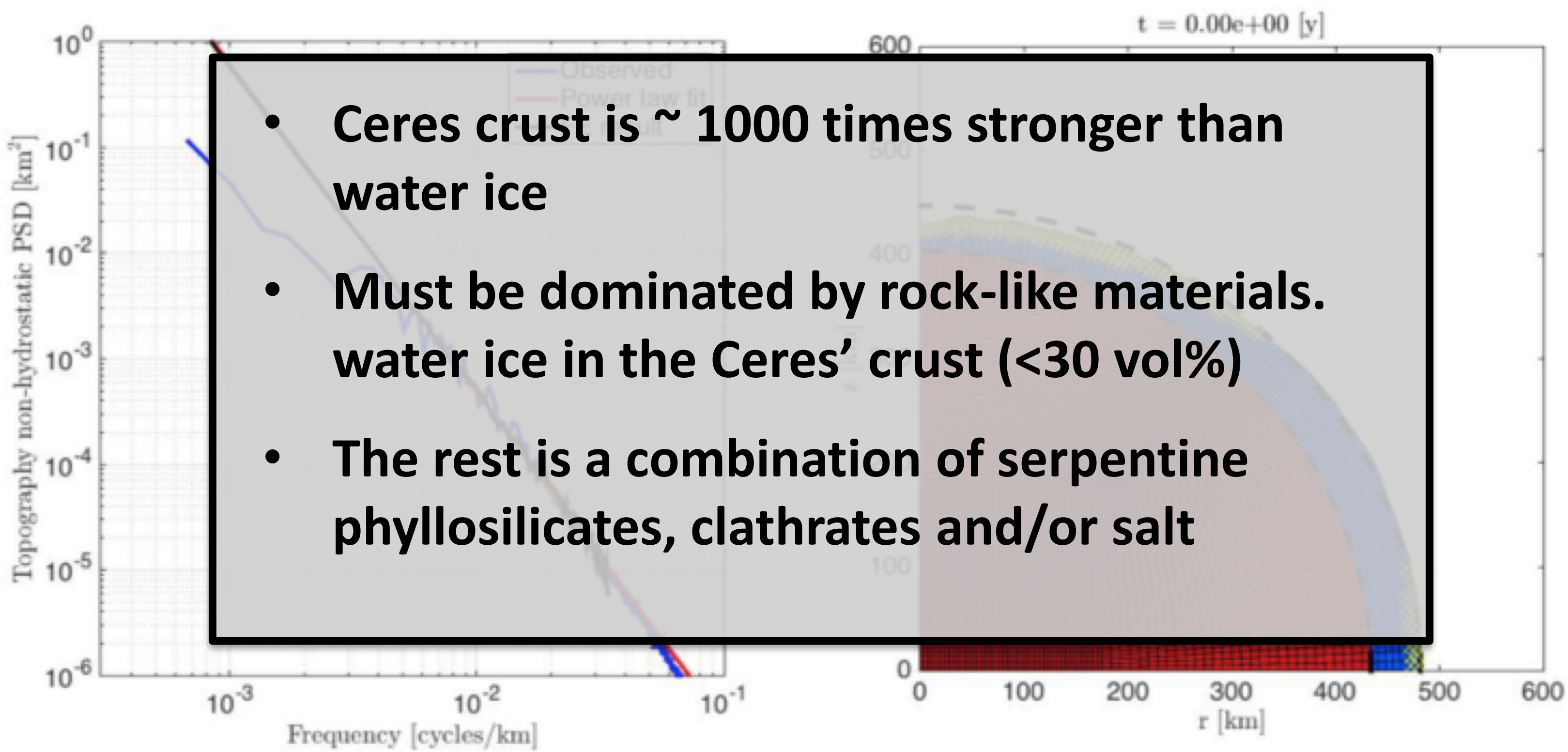
Example of a FE modeling run



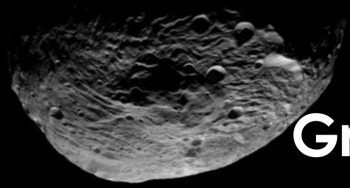




Finite element modeling results



- Ceres crust is ~ 1000 times stronger than water ice
- Must be dominated by rock-like materials. water ice in the Ceres' crust (<30 vol%)
- The rest is a combination of serpentine phyllosilicates, clathrates and/or salt



Gravity and topography in spherical harmonics

- **Shape radius vector**

$$r(\phi,\lambda) = R_0 \left[\sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(A_{nm}\cos(m\lambda) + B_{nm}\sin(m\lambda) \right) P_{nm}(\sin\phi) \right]$$

- **Gravitational potential**

$$U(r,\phi,\lambda) = \frac{GM}{R} \left[1 + \sum_{n=2}^{\infty} \sum_{m=0}^{n} \left(\frac{R_0}{r} \right)^n \left(C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda) \right) P_{nm}(\sin\phi) \right]$$

- **Power Spectral Density**

$$S_n^{gg} = \sum_{m=0}^{n} \frac{C_{nm}^2 + S_{nm}^2}{2n+1}$$

gravity

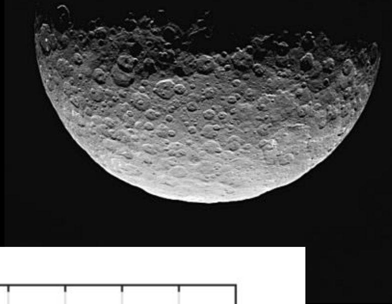
$$S_n^{tt} = \sum_{m=0}^{n} \frac{A_{nm}^2 + B_{nm}^2}{2n+1}$$

topography

$$S_n^{gt} = \sum_{m=0}^{n} \frac{A_{nm}C_{nm} + B_{nm}S_{nm}}{2n+1}$$

gravity-topography cross power

Isostatic model



Z_n - gravity-topography admittance

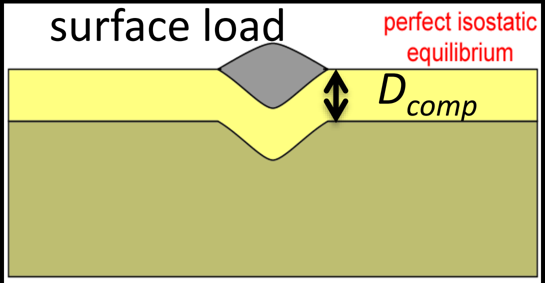
$$Z_n = \frac{S_{gt}}{S_{tt}}$$

- **Linear two-layer hydrostatic model**

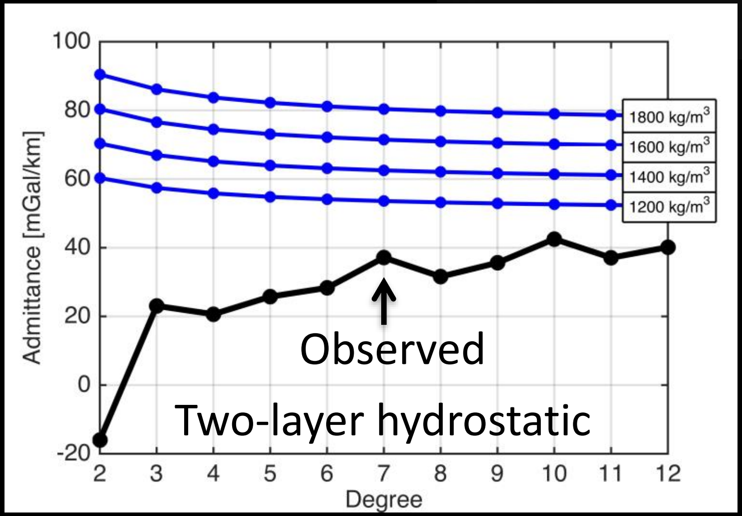
$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}$$

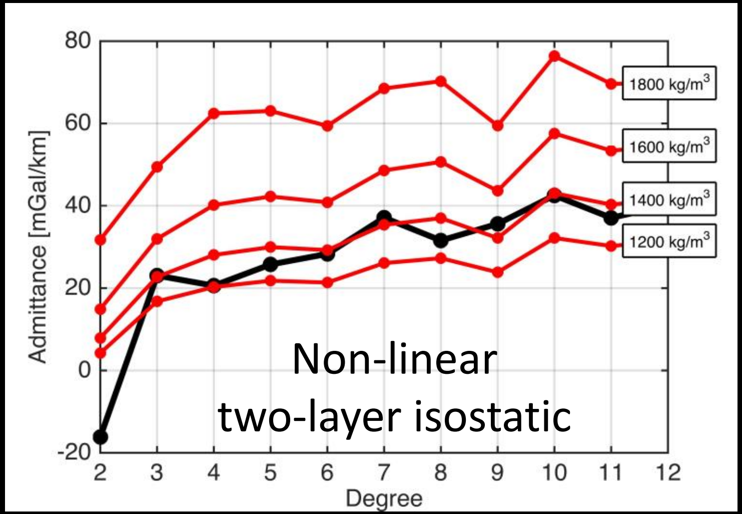
- **Linear isostatic model**

$$Z_n = \frac{GM}{R^3}\frac{3(n+1)}{2n+1}\frac{r_{crust}}{r_{mean}}\left[1-\left(1-\frac{D_{comp}}{R}\right)^n\right]$$



D_{comp}- depth of compensation

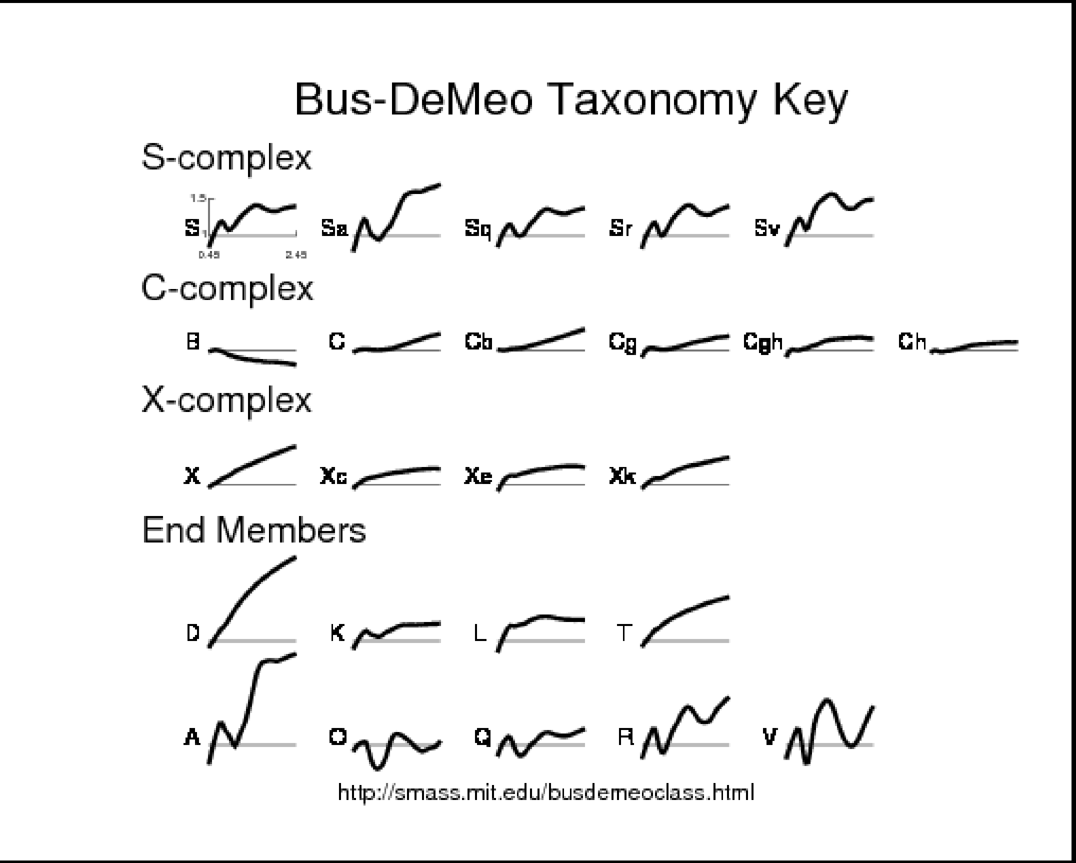


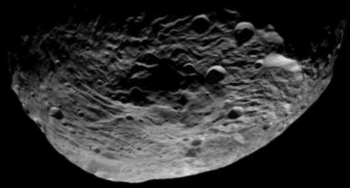


Ermakov et al., Vesta and Ceres interiors,
JpGU-AGU 2017.

Why Vesta?

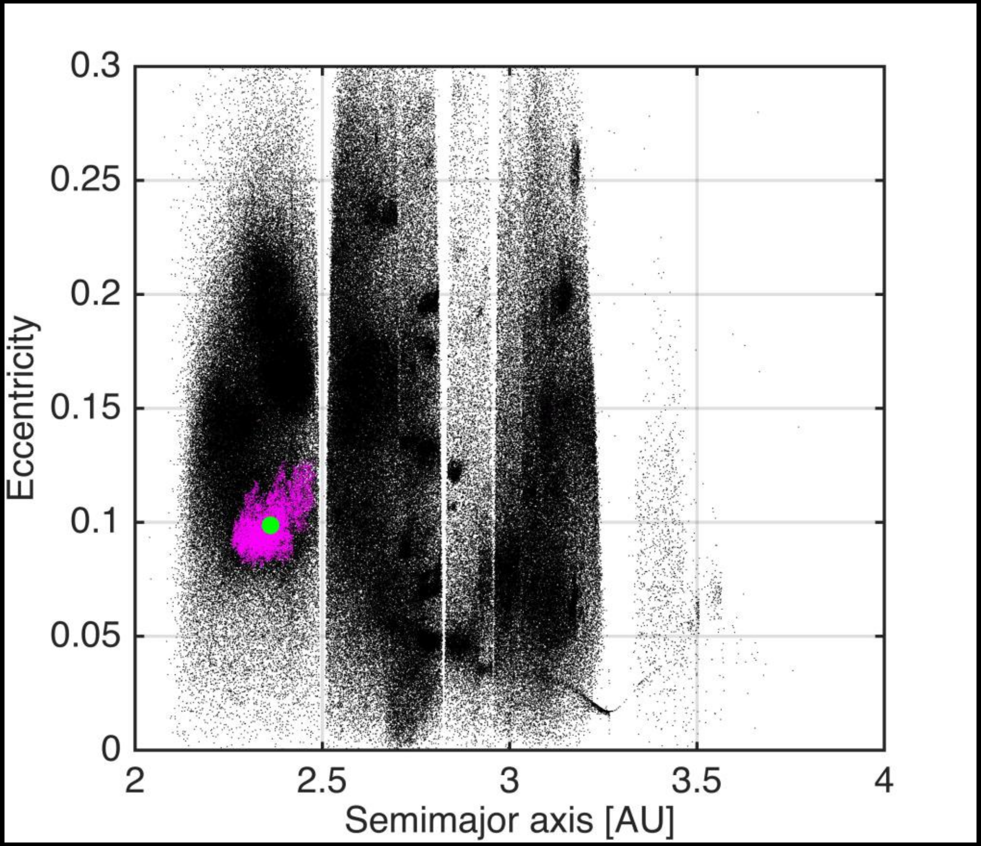
- **Unique basaltic spectrum**





Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**



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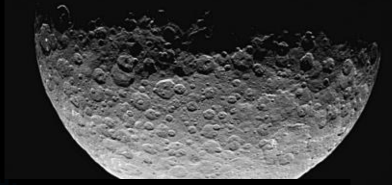


Why Vesta?

- **Unique basaltic spectrum**
- **A group of asteroids in the dynamical vicinity of Vesta with similar spectra**
- **Large depression in the southern hemisphere of Vesta**

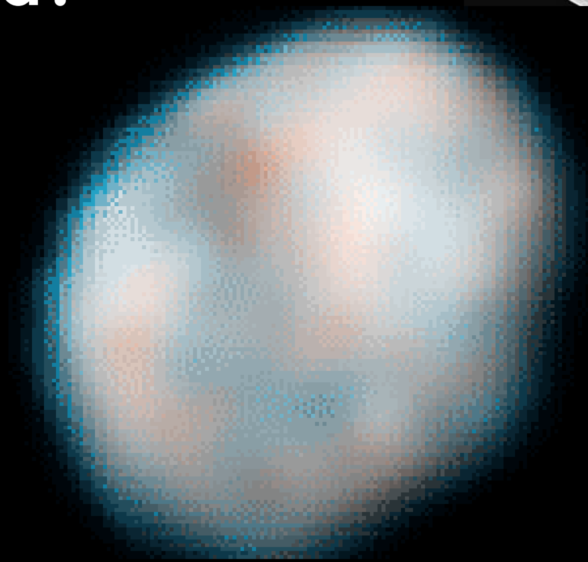
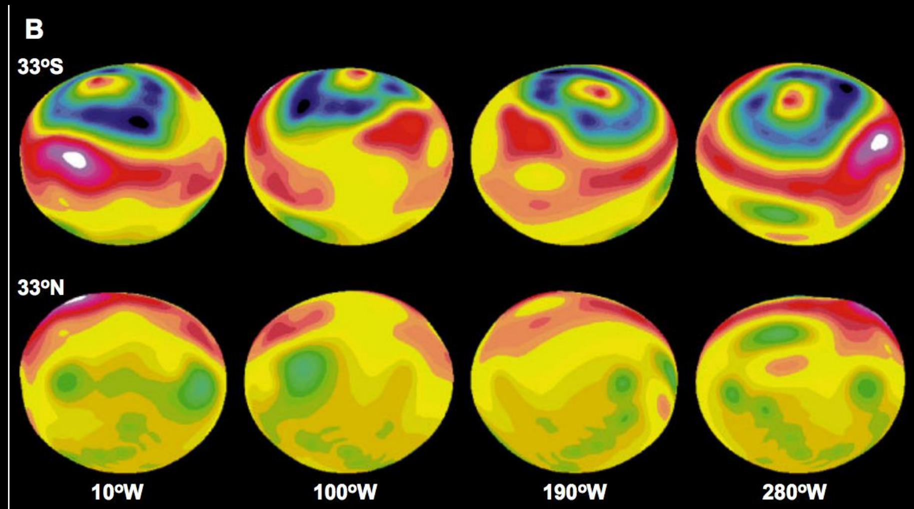
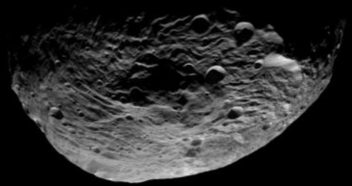


Image credit: NASA/HST

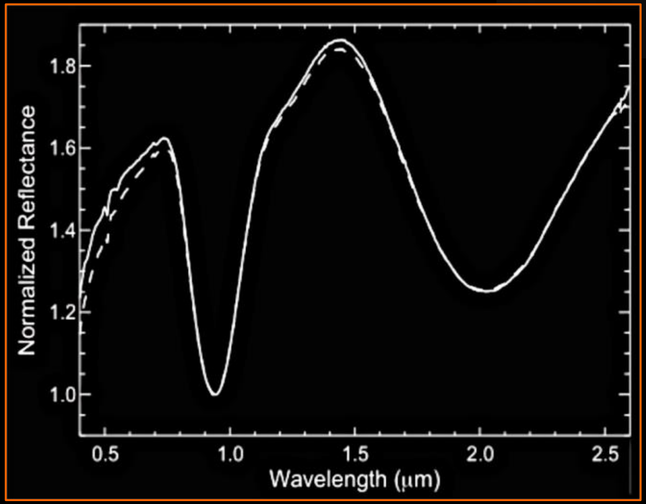


Thomas et al., 1997



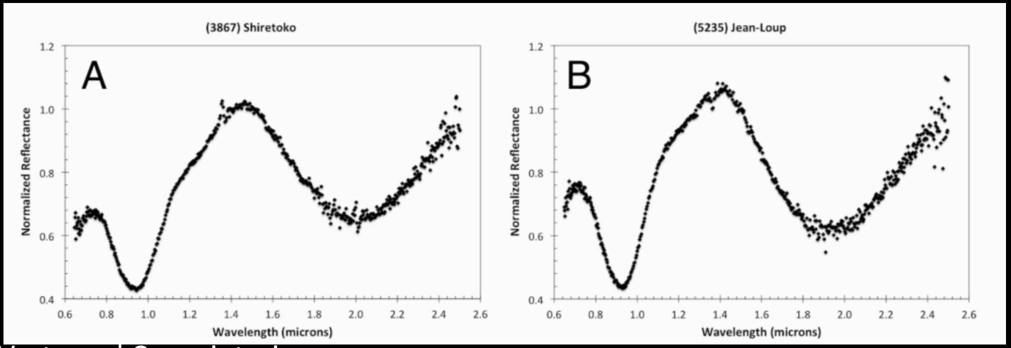
Why Vesta?

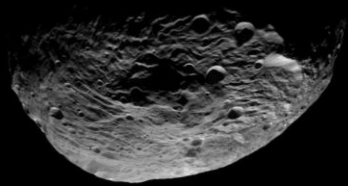
- Unique basaltic spectrum
- A group of asteroids in the dynamical vicinity of Vesta with similar spectra
- Large depression in the southern hemisphere of Vesta
- A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra



↑ Reflectance spectra of eucrite Millbillillie from Wasson et al. (1998)

↓ V-type asteroids spectra from Hardensen et al., (2014)





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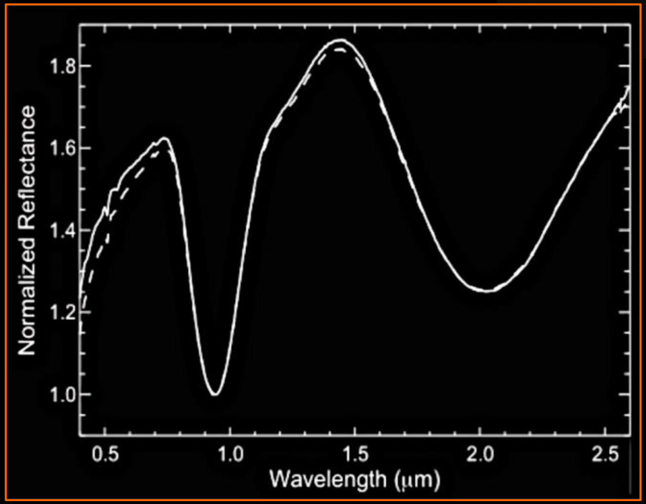
- Large depression in the southern hemisphere of Vesta
- A group of Howardite-Eucrite-Diogenite (HED) meteorites, with similar reflectance spectra
- Strongest connection between a class of meteorites and an asteroidal family



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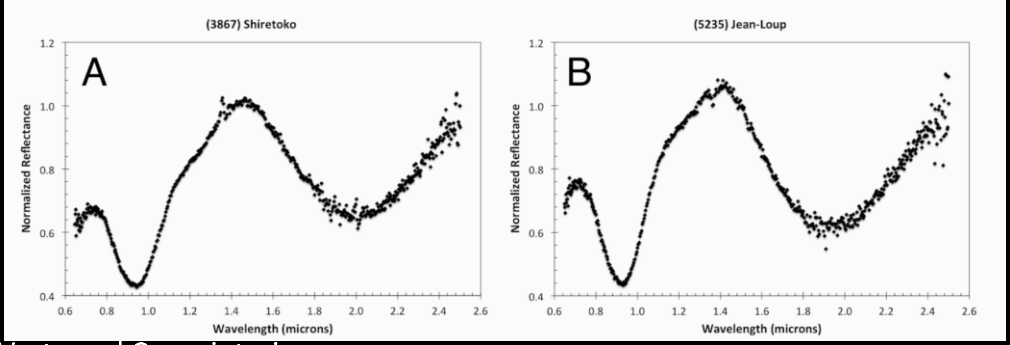

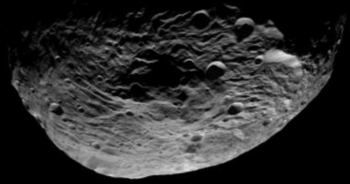

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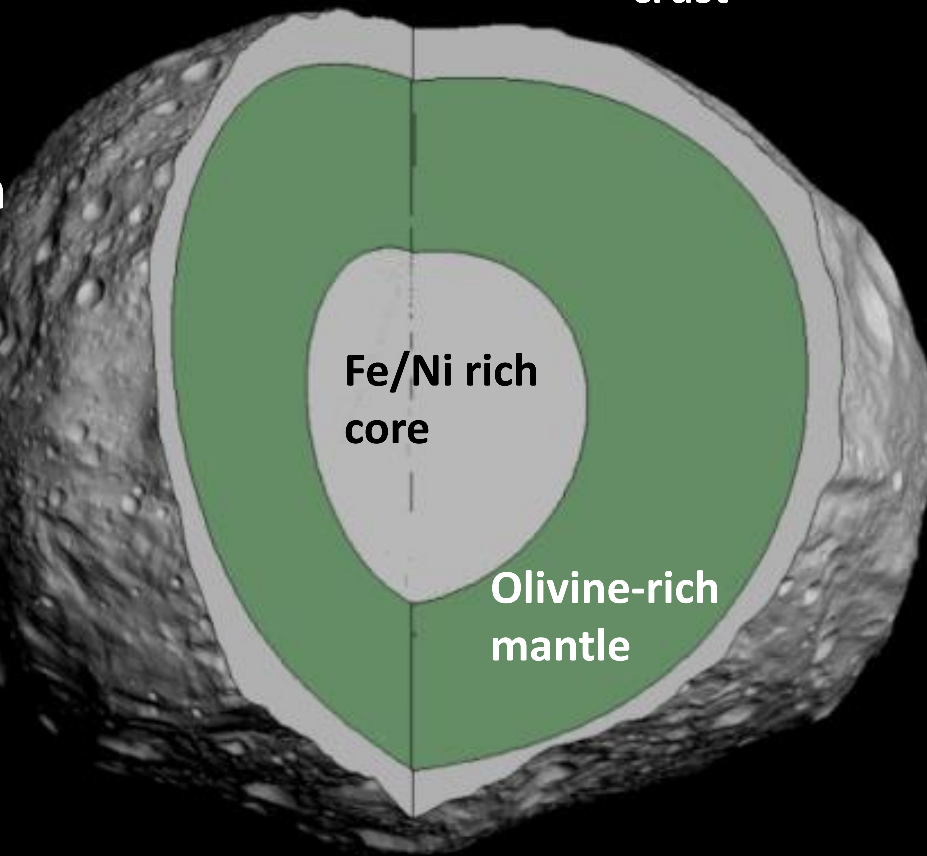
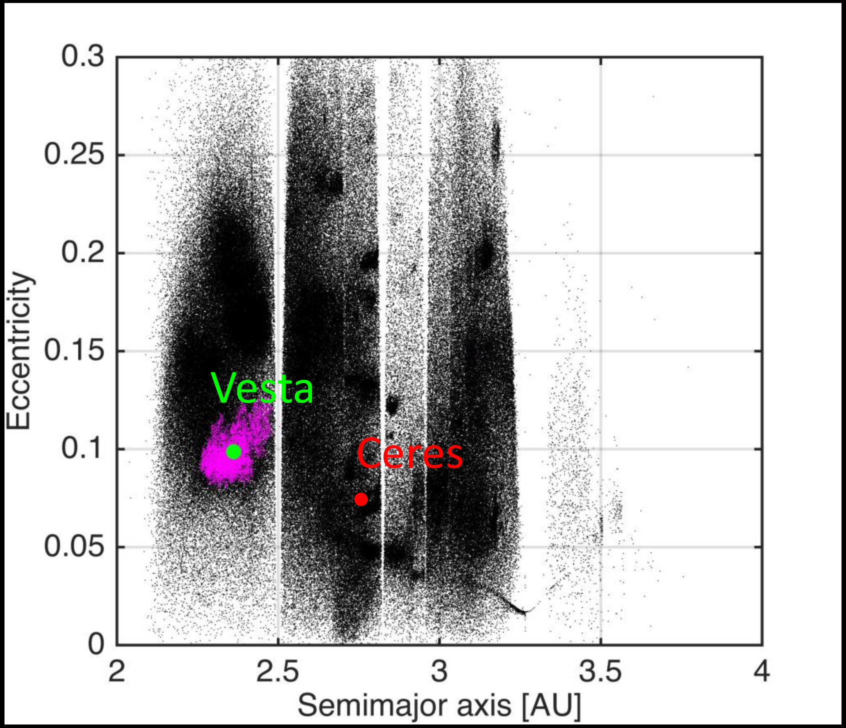
- Densities constrained by the Howardite-Eucrite-Diogenite (HED) meteorites



Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.

Why Ceres?

- Largest body in the asteroid belt
- Low density implies high volatile content
- Conditions for subsurface ocean
- Much easier to reach than other ocean worlds



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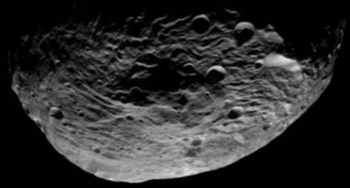


What did we know before Dawn

- **Castillo-Rogez and McCord 2010**

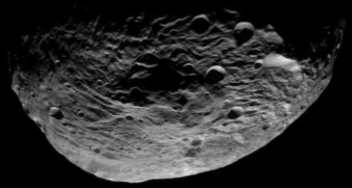
  Ceres accreted as a mixture of ice and rock just a few My after the condensation of Calcium Aluminum-rich Inclusions (CAIs), and later differentiated into a water mantle and a mostly anhydrous silicate core.

- **Zolotov 2009**

  Ceres formed relatively late from planetesimals consisting of hydrated silicates.

- **Bland 2013**

  If Ceres *does* contain a water ice layer, its warm diurnally-averaged surface temperature ensures extensive viscous relaxation of even small impact craters especially near equator



Topography compensation state for Vesta and Ceres

- Vesta topography is <u>uncompensated</u>
- Vesta acquired most of its topography when the crust was already <u>cool and not-relaxing</u>

- Ceres topography is <u>compensated</u>
- Lower viscosities (compared to Vesta) enabled <u>relaxation</u> of topography to isostatic state

Ermakov et al., Vesta and Ceres interiors, JpGU-AGU 2017.