Ceres Differentiation and Composition Constrained Using Moment of Inertia

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Senior Thesis 393

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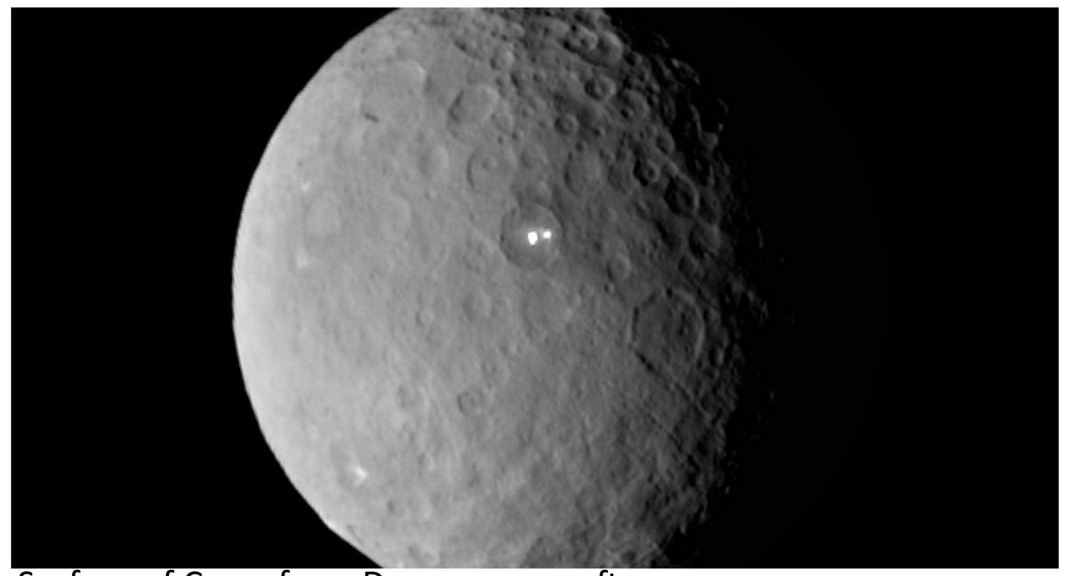
1. Background

NASA launched the Dawn mission in 2007 to rendezvous and orbit Vesta and Ceres and characterize their internal structure, density, shape, size, and mass and returning data on surface morphology, cratering, and magnetism. The data collected during this mission will aid in determining thermal history, size of cores, and the role of water in asteroid evolution.



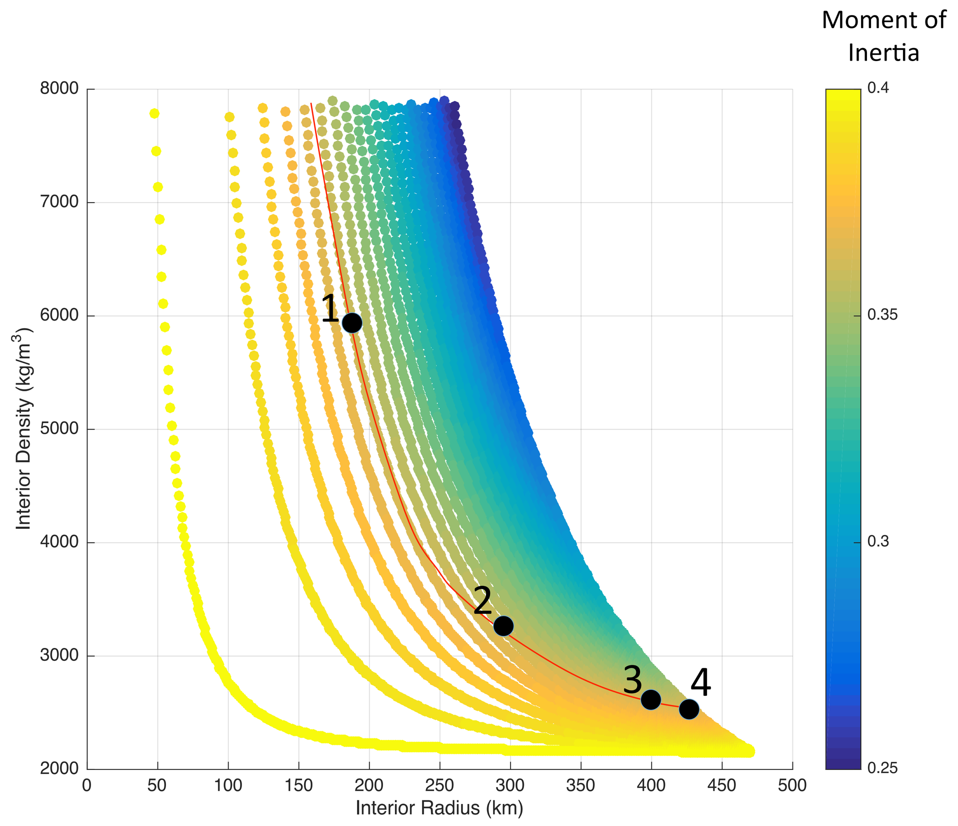
Surface of Ceres from Dawn spacecraft.
Image from dawn.jpl.nasa.gov

Ceres is the largest object in the asteroid belt, with a mass of 9.4 x 10^{20} kg and shape profile of 482 x 480 x 446 km. These measurements result in a bulk density near 2150 kg/m^3 (Neveu and Desch 2016). With a bulk density lower than other silicate bodies, such as Vesta or the Moon, a mixture with less dense materials or porosity is required (Park et al. 2016). The low bulk density has resulted in suggestions of water content between 17 weight % and 35 weight % by mass (McSween et al. 2016, McCord and Sotin 2005). No surface spectra matching water ice has been found (McSween et al. 2016); clay is a better fit, and the Dawn Visible and near-Infrared spectrometer supports this interpretation (Prettyman et al. 2016).

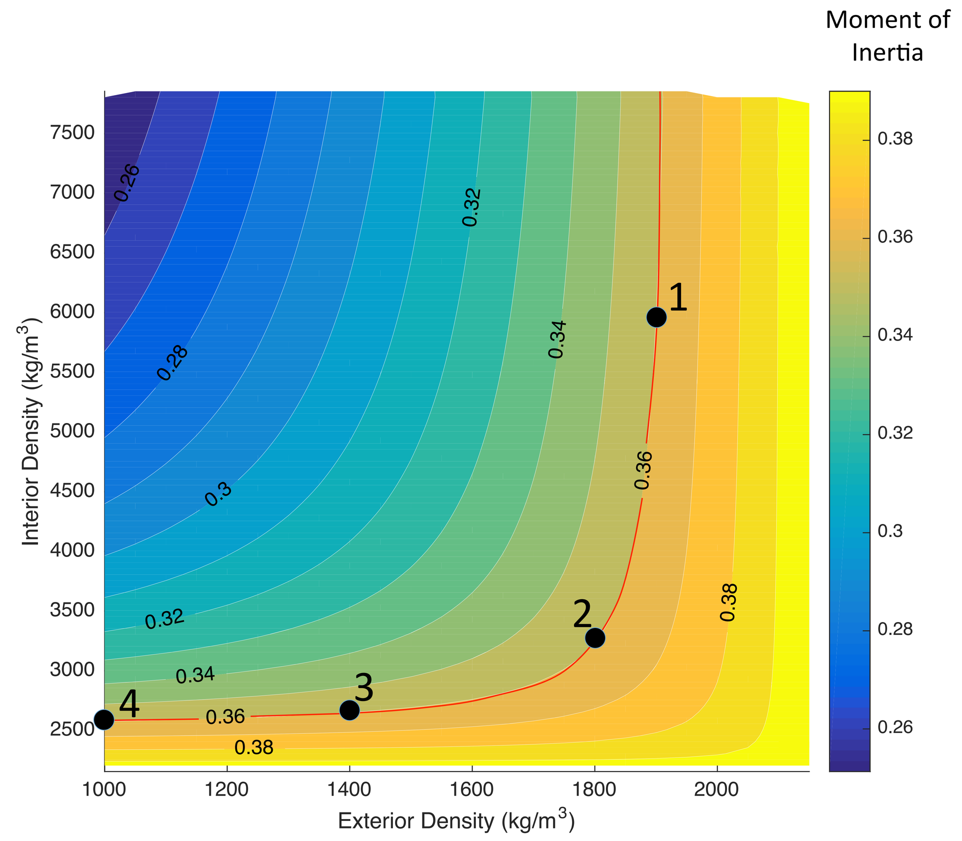
2. Hypothesis

Ceres was differentiated into a body with an interior that has segregated into an exterior and interior of separate and distinct compositions, with volatiles and clay in the exterior and rock or metals in the interior.

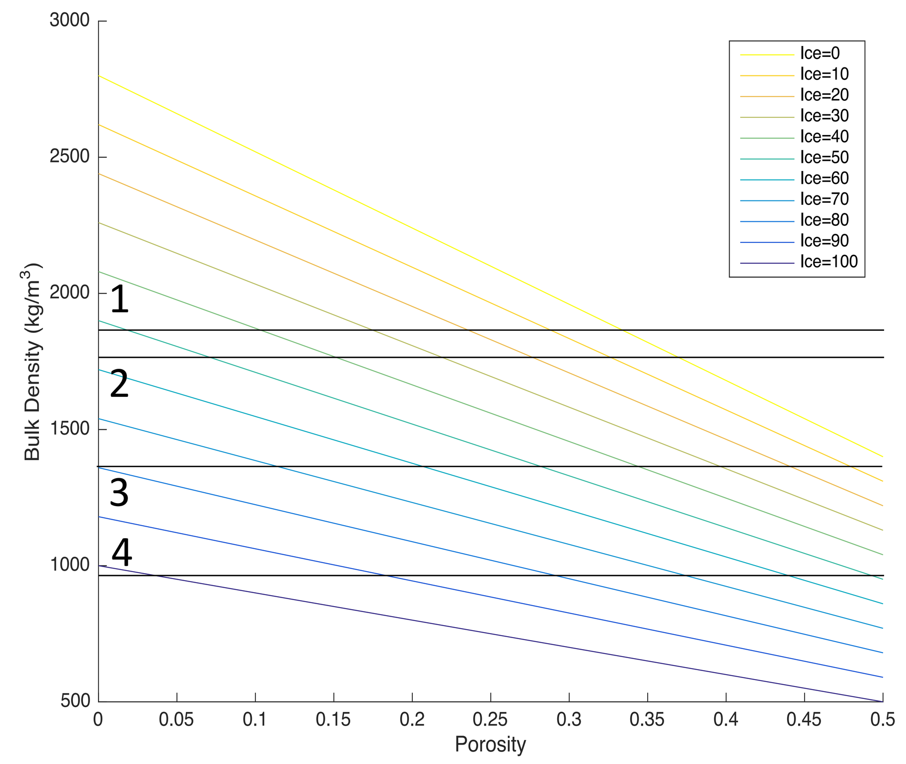
I will test this by modeling the possible internal models of Ceres using known physical parameters such as moment of inertia obtained by the Dawn mission, and by matching this to a range of exterior compositions for a given exterior density.



Interior density and interior radius trade-off. The red line marks a moment of inertia of 0.36, and the points represent the models below.



Exterior density and interior density trade-off. The red line marks a moment of inertia of 0.36, and the points represent the models below.



Relationship between bulk exterior density and the acceptable ice content, rock content, and porosity. Colored lines represent % ice of non-porous material. Black lines represent the exterior densities of the models below.

3. Density Stratification

Using the fixed values of volume, mass, and mean density, a range of values for exterior density, interior density, and interior radius can be calculated. These values are constrained by the moment of inertia of Ceres.

$$\rho_{\text{interior}} = \frac{M_{Total} - \rho_{exterior}\frac{4}{3}\pi r_{Total}^{3}}{\frac{4}{3}\pi r_{\text{interior}}} + \rho_{exterior}$$

$\rho_{interior}$=Interior density
$\rho_{exterior}$=Exterior density
M_{total}=Mass of Ceres
r_{Total}=Radius of Ceres
$r_{interior}$=Interior radius

$$I = \frac{\frac{2}{5} M_{interior} r_{interior}^{2} + M_{exterior}\frac{r_{Total}^{5} - r_{interior}^{5}}{r_{Total}^{3} - r_{interior}^{3}}}{M_{Total} + r_{Total}^{2}}$$

I=Moment of Inertia
M_{total}=Mass of Ceres
$M_{interior}$=Interior mass
$M_{exterior}$=Exterior mass
r_{Total}=Radius of Ceres
$r_{interior}$=Interior radius

4. Composition of the Surface

A three-phase mixing model is used to constrain the fractional composition of the exterior to test the hypothesis that the exterior must contain volatiles to explain the density stratification.

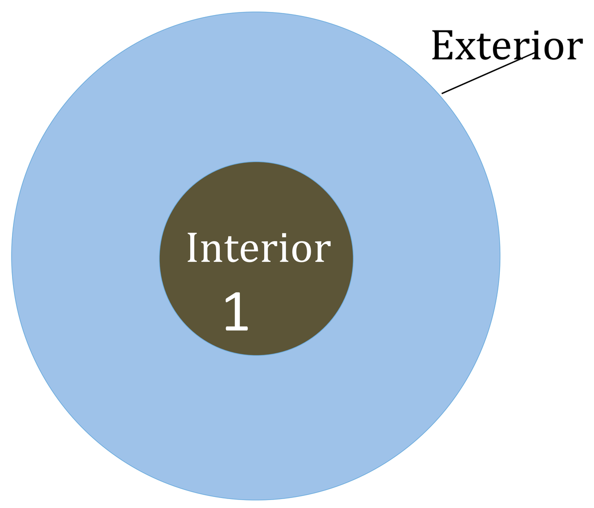
$$\rho_{exterior} = (1 - porosity)((1 - ice)\rho_{clay} + (ice)\rho_{ice})$$

$\rho_{exterior}$=Exterior density
ρ_{clay}=Density of clay
ρ_{ice}=Density of ice

5. Demonstration of Feasibility

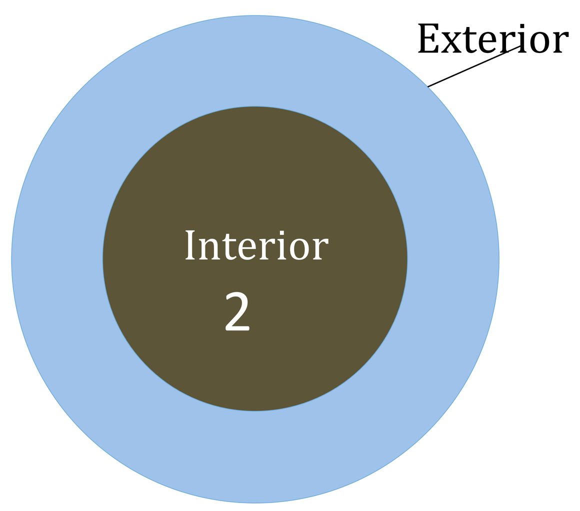
Three models are presented as the preliminary differentiation and compositional models for Ceres. Two of the models represent the high and low extremes of the accepted densities for the interior and exterior, while the third is the median case.

A fourth model, representing an interior of much higher density, is also shown. Previous work does not support such a small interior or high interior density.

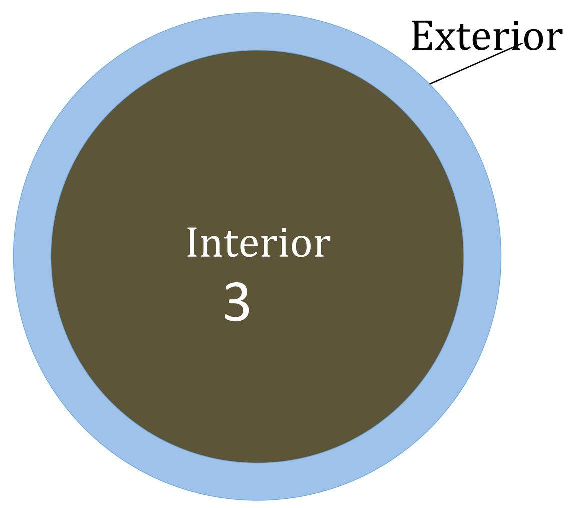


Exterior Density: 1900 kg/m^3
Interior Density: 5977 kg/m^3
Interior Radius: 187 km

- Interior density suggests iron-rich composition
- An iron-rich interior model is not in favor

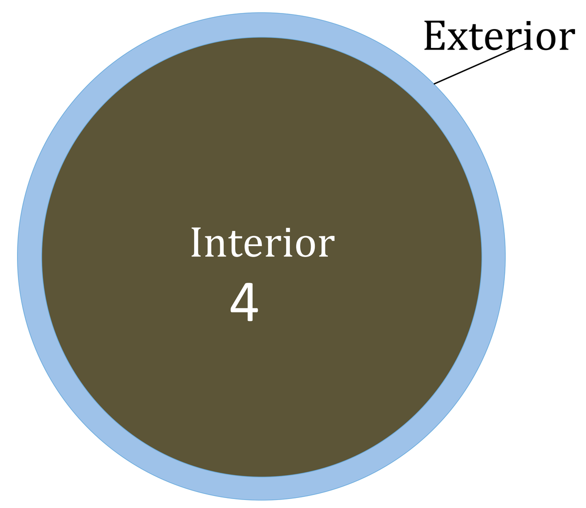


Exterior Density: 1800 kg/m^3
Interior Density: 3259 kg/m^3
Interior Radius: 294 km



Exterior Density: 1400 kg/m^3
Interior Density: 2649 kg/m^3
Interior Radius: 398 km

- These exterior densities represent a range of porosity, ice, and clay
- The interior densities are similar to silicate rock, the favored interior composition
- These models constrain the most likely range of differentiation and composition of Ceres.



Exterior Density: 1000 kg/m^3
Interior Density: 2580 kg/m^3
Interior Radius: 424 km

- Exterior density suggests water ice composition
- This model can be ruled out due to the lack of water ice surface spectra

6. Future Work

Thermal evolution models can show the stability of water phases over time on Ceres and provide the best next step in the project. McCord and Sotin (2005) used thermal evolution models to develop their Ceres internal structures, factoring the decay of ^{26}Al, long-lived radionuclides, and energy effects of mineralization.

This table contains the information used for the modeling for this portion of the project.

	Value	Units	Reference
Mass	9.4062 x 10^{20}	kg	Rambaux et al. 2015
Radius	470.500	km	Rambaux et al. 2015
Volume	4.363 x 10^{17}	m^3	Calculated from Rambaux et al. 2015
Mean Density	2.156 x 10^3	kg/m^3	Calculated from Rambaux et al. 2015
Moment of Inertia	0.36	N/A	Park et al. 2016
Density of Rock	2930	kg/m^3	Carmichael 1982
Density of Ice	1000	kg/m^3	McCord and Sotin 2005
Density of Phyllosilicate Clay	2800	kg/m^3	Carmichael 1982
Density of Iron	7900	kg/m^3	McCord and Sotin 2005

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