**PHOEBE'S SHAPE: POSSIBLE CONSTRAINTS ON INTERNAL STRUCTURE AND ORIGIN.** T. V. Johnson, J. C. Castillo-Rogez, D. L. Matson, P.C. Thomas, [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, Email: Julie.C.Castillo@jpl.nasa.gov, [2] Center for Radiophysics and Space Research, 422 Space Sciences Building, Cornell University, Ithaca, NY 14853.

**Introduction:** Saturn's irregular satellite Phoebe was observed by the Cassini-Huygens spacecraft in June 2004 [1]. Spacecraft tracking and imaging of Phoebe performed during that flyby yielded the mean density and shape of the satellite [1-3]. The mean density, 1629 kg/m$^3$, is greater than the average density of the Saturnian satellites, which led [4] to suggest that Phoebe's solid density could be close to the density of KBOs and Centaurs, i.e., around 1,900 kg/m$^3$, if a 15% allowance is made for porosity. Phoebe's shape has been found by Thomas et al. to be relatively equidimensional, best fit as a somewhat oblate spheroid, not far from that expected for a stratified body in equilibrium with Phoebe's spin. This regular shape, despite the object having been heavily cratered, is intriguing.

Whether or not the observed figure of Phoebe is geophysically meaningful or the random result of collisions has consequences for constraining its origin and internal structure. In this context, it is interesting to note that Saturn's satellite Hyperion, thought to be a collisional fragment of a larger precursor, has a highly non-regular "potato-like" shape despite its mean radius of 135 km. This indicates that this object never had internal temperatures high enough for to relax to a more spherical shape. This suggests that Phoebe's more regular shape results from more than impact processes.

In the following, we consider possible thermal evolution scenarios for Phoebe depending on conditions in the outer solar system, and discuss the potential information contained in the shape.

**Interpretation of Phoebe's Shape:** Thomas et al. [3] have determined fits for Phoebe's principal axes. The mean radius is equal to 106.5±0.7 km, and the main radii are: a = 108.6±0.7 km, b = 107.7±1.4 km, c = 101.5±0.3 km. Phoebe's fit shape is close to an oblate spheroid, with a~b to within the uncertainties. If this shape indeed reflects a hydrostatic response to spin stresses, we can draw some conclusions about its internal structure and history. Phoebe's shape is also affected by large, unrelaxed impact craters. These provide over 15 km of relief relative to equipotentials calculated with or without a differentiated structure. Phoebe's spin period is 9.27 hrs [5]. The corresponding equilibrium difference between the equatorial and polar radii (*a-c*) if Phoebe were homogenous and hydrostatically relaxed would be about 10.7 km. The data indicate a value of (*a-c*) = 6.7 ± 1.1 km, within the uncertainties.

This difference suggests some degree of concentration of mass toward the center. This could be due either to porosity compaction, or to stratification due to a rock-rich core below an icy shell resulting from differentiation as a result of internal melting. We compare a range of possible models in these two categories against the observed value of $(a - c)$.

**Thermal Evolution Models:** We follow the modeling approach by [6]. We assume that Phoebe could have formed within a few My after the production of calcium-aluminum inclusions (CAIs), i.e., contemporaneously with the parent bodies of carbonaceous chondrites. We also test the thermal evolution of models formed later than 5 My after CAIs.

We [7] have suggested that large outer planetary bodies such as KBOs could have formed from planetesimals that were affected by $^{26}$Al decay heat. The latter induced a redistribution of elements between the rocky and volatile phases in a hydrothermal context. Impurities in the volatile phase could have decreased the thermal conductivity and the melting temperature. In absence of other constraints we assume in all our models the presence of ammonia hydrates whose creep activation temperature is about 100 K and melting temperature is 176 K. Models start with porosity profiles constrained by experimental measurements (e.g., [8, 9]) and modified by the calculated thermal profiles. We compute the actual silicate mass fraction for compacted material following the approach described in [6].

For models assuming a time of formation 5 My after after CAIs (Figure 1-i), the internal temperature barely gets above 100 K. As a result only the deep-seated internal porosity is decreased somewhat and the model preserves an outer layer about 15 km thick that is undifferentiated and highly porous. In these models, we infer a density for the compacted material of ~2000 kg/m$^3$, which is consistent with the suggestion by [4] that Phoebe's "solid" density is close to the mean density found for Kuiper-Belt objects. However, the corresponding value for the hydrostatic $(a - c)$ is greater than 9 km, which is inconsistent with the observed oblateness

For models with earlier times of formation (Figure 1-ii) the heat from $^{26}$Al leads to rapid internal melting and differentiation. With the absence of other

significant heat sources, Phoebe probably froze in less than 100 My after formation. The final internal structure is the same for all formation times less than 4 My after CAIs. However, a melting point depressant, such as ammonia, is necessary for melting the ice if the formation times are greater than 3.5 My. Melting driven by $^{26}Al$ decay heat could have been accompanied by hydrothermal and geochemical activity, as has been suggested for meteorite parent bodies (e.g.[10]). This category of model also has a thin (5-10 km thick), porous, icy layer whose thickness is a function of the initial surface temperature. (Note that in either model, macroproosity from cratering may exend to greater depth and has not been accounted in our models.)

The corresponding hydrostatic shapes for these models have an *(a – c)* between 6.8 and 8 km, consistent within errors with the observed oblateness. (Note however, that we find no realistic models with an *(a – c)* as small as the lowest values allowed by the uncertainties.)

**Implications for Phoebe's Origins:** Our models are consistent with the suggestion by [4] that Phoebe's solid density is ~1900 kg/m$^3$ with the presence of 10-20% of porosity, thus very different from the mean density of the Saturnian satellites.

Since there is a range of possible solid densities and porosity structures, we cannot determine a unique internal structure for Phoebe, even with the assumption of an equilibrium hydrostatic shape. We can draw some general conclusions, however:

First, cold relatively homogeneous internal models, even with porosity, do not match the observed oblateness for a hydrostatic figure. In addition, such cold models are less likely to have relaxed to a hydrostatic figure because their internal temperature could not reach the water creep temperature. For such models, Phoebe's oblate shape must be assumed to be a coincidence of impact 'sculpting'.

Second, if Phoebe formed early enough to have significant heating from $^{26}Al$ (before ~4 My after CAIs), a plausible and consistent (but not unique) picture is that it is a body that formed in the outer planetesimal disk contemporaneously with carbonaceous chondrites, with a density ~2000 kg/m$^3$ and has a layered internal structure from at least partial differentiation, consistent with a hydrostatic shape matching the observed oblateness. If so it may be typical of many objects in the outer solar system including the present KBOs, TNOs.

**Acknowledgements:** Part of this work has been carried out at the Jet Propulsion Laboratory, California Institute of Technology. Copyright Caltech. Government sponsorship acknowledged.

**References:**

[1] Porco, C. C., et al. (2005) *Science* **307**, 1237-1242. [2] Jacobson, R. A., et al. (2006) *Astronomical Journal* **132**, 2520-2526. [3] Thomas, P. C., et al. (2006) *Eos Tans. AGU* **87(52)**, Fall Meet. Suppl., Abstract P32-01. [4] Johnson, T. V. and J. I. Lunine (2005) *Nature* **435**, 69-71. [5] Bauer, J. M., et al. (2004) *Astrophysical Journal Letters* **610**, L57-L60. [6] Castillo-Rogez, J. C., et al. (2007) *Icarus* **190**, 179-202. [7] Castillo-Rogez, J. C., et al. (2008) *Bull. Am. Astron. Soc.* **40**, 58.04. [8] Durham, W. B., et al. (2005) *Geophys. Res. Lett.* **32**. [9] Leliwa-Kopystynski, J. and K. J. Kossacki (2000) *Planet Space Sci.* **48**, 727-745. [10] Grimm, R. E. and H. Y. McSween (1989) *Icarus* **82**, 244-280.

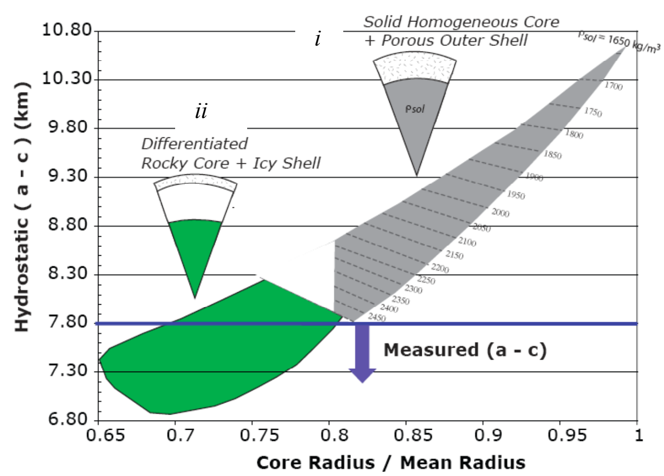


**Figure 1.** Theoretical *(a-c)* values as a function of the core radius to mean radius ratio for possible models for Phoebe. This calculation is compared against the measured *(a-c)* assuming hydrostatic equilibrium. (i) Undifferentiated model with a solid density higher than the measured mean density and a porous icy shell with porosity ranging between 20 and 40%. (ii) Multilayered model composed of a rocky core, icy shell and a porous outer layer with porosity ranging between 25 and 40%. The core may be composed of anhydrous silicate with a density between 3200 and 3500 kg/m$^3$ and/or hydrated silicate with a density between 2500 and 3000 kg/m$^3$.