HOW DIFFERENTIATED IS CALLISTO? J. C. Castillo-Rogez[1], J. I. Lunine[2], and T. V. Johnson[1], [1]Jet Propulsion Laboratory, California Institute of Technolgoy, Pasadena, CA, United States (jccastil@jpl.nasa.gov), [2]Dipartimento di Fisica, Università degli Studi di Roma "Tor Vergata", Rome, Italy. (jlunine@roma2.infn.it).

Introduction: The model of Callisto as a partially differentiated ice/rock body, designed to fit the relatively large moment of inertia (MoI) inferred from *Galileo* data, has played a key role in defining the current landscape of satellite accretion models. The gas-poor subnebula model [1] was in part motivated by the dichotomy between Ganymede and Callisto, primarily expressed in the contrast in the MoI values characterizing each object. However, we argue that the observational evidence behind this widely accepted model is weak, by suggesting an alternative interpretation of the *Galileo* gravity data. In our model, Callisto has differentiated an icy shell and rocky core, and in the latter a large fraction of the accreted water is stored in the form of water of hydration. This model is consistent with the observed moment of inertia, supported by experimental measurements, and with geophysical constraints inferred from Callisto's geological history.

Galileo's Gravity Data: At the core of the problem is the assumption that Callisto is in hydrostatic equilibrium, which was used as the basis for interpreting gravity data provided by the *Galileo* Mission. Before *Galileo* reached the Jovian system it was explicitly noted [2] that the possibility of non-hydrostaticity could make ambiguous the interpretation of gravity data. As a matter of fact, the available dataset, while scarce, does present a number of anomalies suggesting that the moon is not in hydrostatic equilibrium.

First, the value of the mean moment of inertia significantly decreased as more gravity data became available, starting from 0.416±?? after two flybys [3] to 0.354 9±0.004 2 from combining the whole set of four flybys [4]. The error bars inferred from successive solutions do not overlap, and the actual error on the MoI used in geophysical studies is not constrained, since it can only account for systematic effects. The ratio of the degree-coefficients J_2 to C_{22} is close to 1/3, which suggests that the satellite is hydrostatically relaxed. However, the correlation coefficient between the two parameters is equal to 0.997, because all the the gravity passes were performed in Callisto's equatorial plane. Since C_{22} has not been determined independently from J_2, it is not clear whether their 1/3 ratio reflects the actual state of the satellite or is an artificial result of the inversion procedure. The most obvious indication of a departure from hydrostaticity is the existence of a non-zero S_{22} coefficient that amounts to 10% of C_{22}. That anomalous parameter was previously noted [5] but its importance has been overlooked in geophysical studies aimed to interpret the gravity data. As a comparison, the S_{22} determined for Titan from gravity measurements with the *Cassini* spacecraft is only ~2% of C_{22} [6]. Titan's MoI was found as 0.341 9±0.000 5, but the potential role of non-hydrostatic anomalies was acknowledged by [6], and a lower bound on the MoI estimated as 0.335. More generally, departures from hydrostaticity has been observed at many satellites: Ganymede [7], Rhea [8], even the geologically active Enceladus [9]. All these pieces of information motivate us to question the validity of the hydrostaticity assumption and the small error bar of the MoI value used in geophysical models of Callisto. We argue that a MoI value lower than 0.35 cannot be rules out, based on the data.

Unfortunately, we lack observations complementary to the gravity data that would allow testing of the geophysical models. The difficulty to preserve a undifferentiated core was noted, but solutions were proposed [10]. Geological data suggest that Callisto's outer shell is ice-dominated at least 80-km thick [11], while an induced magnetic field [12] points to the presence of a deep ocean and hence a significant amount of internal heating. Unfortunately, the *Galileo* MAG data are not accurate enough to yield further constraints on the structure of the hydrosphere (shell thickness, ocean density) as could be done for Europa [13].

Interior Model: Two configurations can lead to a relatively large moment of inertia: a large core dominated by a mixture of ice and rock, or a fully differentiated body in which large amounts of water are chemically bound to the silicates as water of hydration. In the case of Titan, we showed [14] that the observed MoI [6] can be interpreted as evidence for a core enriched in hydrated silicates, as previously suggested [15], and demonstrated the long-term stability of hydrated silicates until present.

Aqueous alteration of silicates in contact with water is a pervasive process [16], widely recorgnized as responsible for the abundance of hydrated silicates in carbonaceous chondrite parent bodies [17], Phoebe [18], at the surface of KBOs [19], possibly responsible for the widespread presence of hydrated silicates detected in exoplanetary systems [20], and suggested in Galilean satellites in many studies [e.g., 21, 22]. Abundant hydrated silicate in Ceres' core was also inferred from shape data [23], and found consistent with available MoI data at Ganymede [16].

In the case of Callisto, we show that a core dominated by hydrated silicates is characterized by a moment of inertia of 0.342-0.349, which is consistent with the observed value given our arguments about error sources discussed above. As is the case of Titan, we demonstrate that hydrated silicates can be stable in Callisto's core until present.

Implications: We have devised tests of our model to be carried out by future missions to the Jovian system. For example, our model implies that the core could be dehydrating [14], although this depends on several parameters determining the long-term evolution of the object. The heat pulse associated with that dehydration event would result in the destabilization of the high-pressure ice layer and the gradual thinning of the ice shell, possibly leading to the relaxation of geological features, and even resurfacing. High resolution imagery could reveal such features. Our model is also consistent with the long-term preservation of a deep ocean, promoted by its enrichment in impurities as a natural consequence of silicate serpentinization, as well as the presence of ammonia suggested by cosmochemical models [24]. The existence of an induced magnetic field [12] also points to the presence of impurities in Callisto's ocean [13].

Our picture has implications for the early history of the Jovian system and indeed the solar system as a whole. Our models of Titan and Callisto require their accretion within a few My after the formation of calcium-alunimum inclusions in order for short-lived radioisotopes decay to be geophysically significant and promote hydrothermal activity. While there is growing observational evidence and theoretical agreement that ^{26}Al was widespread throughout the Solar system [e.g., 25], and that the Saturnian system formed in 3 to 4 My [26, 27], the smoking gun for the accretion of ^{26}Al in giant planet satellites remains to be discovered. However, recent modeling has suggested that Saturn's rings could have formed from a differentiated Titan-like object [28], which is consistent with the accretional conditions adopted in our modeling approach.

References: [1] Canup, R. and Ward, W. (2002) *AJ, 124,* 3404-3423. [2] Mueller S. and Mkicnnon W. B. (1988) *Icarus*, 76, 437-464. [3] Anderson J. D. et al. (1997) *Nature*, 387, 264-266. [4] Anderson J. D. et al. (2001) *Icarus*, 153, 157-161. [5] Schubert G. et al. (2004) In: *Jupiter. The planet, satellites and magnetosphere.* Eds: F. Bagenal et al. Cambridge planetary science, Cambridge, UK: Cambridge University Press, 281 - 306. [6] Iess L. et al. (2010) *Science*, 327, 1367-1369. [7] Palguta J. et al. (2006) *Icarus*, 180, 428-441. [8] MacKenzie R. A. et al. (2008) *GRL*, 35, L05204. [9] Schenk P. and McKinnon W. B. (2008), *LPS XXXIX*, abstract #2523. [10] Nagel K. et al. (2004) *Icarus*, 169, 402–412. [11] Schenk P. M. (2002) *Nature*, 417, 419-421. [12] Zimmer C. et al. (2000) *Icarus*, 147, 329-347. [13] Hand K. P. and Chyba C.F. (2007) *Icarus*, 189, 424-438. [14] Castillo-Rogez J. C. and Lunine J. I. (2010) *GRL*, 37, L20205. [15] Engel S and, Lunine J. I. (1994) *JGR*, 99, 3745-3752. [16] Scott H. P. et al. (2002) *EPSL*, 203, 399-412. [17] Grimm R. E. and McSween, H. Y. (1989) *Icarus*, 82, 244–280. [18] Cruikshank D. P. et al. (2008) *Icarus*, 193, 334-343. [19] Busarev V. V. et al. (2003) *Earth, Moon, and Planets*, 92, 345-375. [20] Morris M. A. and Desch, S. J. (2009) *AsBio*, 9, 965-978. [21] Ransford G. A. et al. (1981) *Nature*, 289, 21-24. [22] Vance S. et al. (2007) *AsBio*, 7, 987-1005. [23] Thomas P. C. et al. (2005) *Nature*, 437, 224-226. [24] Lunine, J.I. and Stevenson, D.J. (1982) *Icarus 52*, 14-39. [25] Ouellette N. et al. (2010) *ApJ*, 711, 597-612. [26] Dodson-Robinson S. et al. (2008) *ApJ*, 688, L99. [27] Castillo-Rogez et al. (2009) *Icarus* 204, 658-662. [28] Canup R. M. (2010) *Nature*, doi:10.1038/nature09661.

Acknowledgements: Part of this work has been conducted, for JCC, at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration, and for JIL under the program "Incentivazione alla mobilita' di studiosi straineri e italiani residenti all'estero" of Italy.