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The Ganymede-Callisto Dichotomy: Constraints from *Galileo* and *Cassini*

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Abstract

Neither Callisto nor Titan appear to be fully differentiated, which implies that Ganymede 1) may have accreted in no more than a partially differentiated state as well, and 2) would not have completely differentiated "on its own" (i.e., due to radiogenic heating). If this is true, then tidal heating must be invoked to drive differentiation to completion, which may be connected to the epoch of bright grooved and smooth terrain formation as well as the present generation of Ganymede's intrinsic magnetic field. Of all the proposed tidal histories for the Galilean satellites, only the temporary capture into Laplace-like resonances, originally proposed by Malhotra and Showman, provides geophysically significant amounts of tidal heating to Ganymede.

Moments of Inertia (MOI)

Based on *Galileo* gravity, Ganymede's normalized MOI of 0.3115 is consistent with full differentiation [1], whereas Callisto's value of 0.355 implies an extent of differentiation between ≈20% [2] and ~40% [1], depending on whether Callisto has a hydrated rock core. *Cassini* gravity has recently determined Titan's normalized MOI ≈0.34 [3], an intermediate case (at least ≈40% differentiated), and nonhydrostatic contributions to the gravity are also seen [3]. For Callisto the above calculations assume hydrostaticity, but we note that the scale of the nonhydrostatic contribution at Ganymede [4], if applied to Callisto, would not change the fundamental conclusion (partial differentiation).

The implications for accretional conditions have been clear for some time: for a body the scale of Callisto to remain undifferentiated (or nearly so) requires 1) slow accretion (>10^6 yr), a radiation cooling limit; 2) small satellitesimals (<10-m diameter), a conductive burial limit; and 3) accretion completed no earlier than ≈3 Myr after the condensation of calcium-aluminium inclusions (in the inner Solar System), to limit short-lived radioisotope heat release [5,6,7]. These accretion duration and size constraints are treated in detail in [8]. The constraints are consistent with the "gas-starved" disk model for satellite formation, which postulates declining solar nebula influx across a tidal gap to form an accretion disk around each of Jupiter and Saturn [9,10,11].

Ganymede

Early models of Ganymede's formation [5,12] postulated rapid accretion and a deeply melted beginning, followed by overturn into a three-layer structure [2,13]. The modern view of the jovian (and saturnian) subnebulae does not provide for so hot an origin, nor are surface oceans necessarily stable against freezing at the surface in these subnebulae. For three-layer structures, subsequent differentiation of the intermediate ice-rock layer is thus problematic (it was never obvious or easy), because the melting curve of deep, high-pressure ice VI and VII rises rapidly with pressure. Solid-state separation of rock lumps from ice is possible in principle [14], but the size spectrum of rocky "particles" is unknown and such differentiation is unlikely to ever be 100% efficient (small particles will always remain entrained in the ice).

The Laplace Resonance

The advantage Ganymede has over both Callisto and Titan is that, as part of the Laplace resonance with Io and Europa, Ganymede may have been strongly tidally heated in the past (even if it is not being significantly heated now). Proposals for the assembly of the Laplace resonance have evolved over the years, from the classic inside-out assembly due to differential tidal expansion [15] to outside-in assembly due to type I drift in the jovian subnebula [16]. In both of these scenarios, how-

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ever, Ganymede's eccentricity is not strongly excited, except transiently during the final assembly of the resonance between all three satellites.

Malhotra [17] and Showman and Malhotra [18] proposed that during satellite orbital expansion, but before the Laplace resonance was achieved, all three satellites temporarily occupied various "Laplace-like" resonances. While in such temporary resonances, Ganymede's eccentricity may have been excited to the several percent level. The possible implications for Ganymede's active geologic history and extant magnetic field have been explored, most recently in [19,20]. While several important aspects of Ganymede's evolution remain to be worked out, especially with regard to its magnetic field, this scenario appears especially promising in regard to grooved terrain formation. Models of the later have long indicated rather high heat flows if not access to liquid water [21,22,23], and which are hard to rationalize in the absence of tidal heating.

An important question on the theory side is how could the Laplace resonance have avoided primordial formation [11]? Type I drift is proportional to both satellite and nebular surface density, so perhaps despite Ganymede's much greater mass than Europa, it was unable to catch up with Europa before the solar nebula inflow ended (gap opening for Ganymede is another possibility). Or perhaps Europa originally possessed a thicker ice shell, only to lose it during the late heavy bombardment [24].

Role of JGO

Neither Callisto nor Titan possess an intrinsic magnetic field, and *Galileo* images did not reveal any ancient epoch of grooved terrain resurfacing on Callisto. Titan betrays some parallel tectonic elements [25], but nothing so far that resembles the structural patterns in Ganymede's sulci (though erosion and burial of relatively low-lying terrains on Titan may impair such recognition). Substantial improvements in understanding how Ganymede differs from its sister Callisto and cousin Titan would come from a truly global high-resolution imaging and topographic measurement campaign, as well as global higher-order gravity, at Ganymede, and establishing the degree of hydrostatic equilibrium for Callisto. Both could be accomplished with the proposed JGO mission.

References

[1] Schubert, G. et al. (2004) in *Jupiter – The Planet, Satellites and Magnetosphere* (Bagenal, F. et al., eds.) CUP, 281–306.

[2] Mueller, S. and McKinnon, W.B. (1988) *Icarus*, 76, 437–464.

[3] Rappaport, N. et al. (2008) Fall AGU abs. #P21A-1343.

[4] Palguta, J. et al. (2006) *Icarus*, 180, 428–441.

[5] Stevenson, D.J. et al. (1986) in *Satellites* (Burns, J.A. and Matthews, M.S., eds.) UAP, 39–88.

[6] McKinnon, W.B. (2004) *BAAS*, 36, abs. #40.15.

[7] McKinnon, W.B. (2006) *LPS XXXVII,* abs. #2444.

[8] Barr, A.C. and Canup, R.P. (2008) *Icarus*, 198, 163–177.

[9] Canup, R.M. and Ward, W.R. (2002) *Astron.J.*, 124, 3404–3423.

[10] Canup, R.M. and Ward, W.R. (2006) *Nature*, 441, 834–839.

[11] Peale, S.J. (2007) in *Treatise on Geophysics, vol. 10* (Spohn, T., vol. ed.) Elsevier, 465–508.

[12] Lunine, J.I. and Stevenson, D.J. (1982) *Icarus*, 52, 14–39.

[13] McKinnon, W.B. and Parmentier, E.M. (1986) in *Satellites* (Burns, J.A. and Matthews, M.S., eds.) UAP, 718–763.

[14] Nagel, K. et al. (2004) *Icarus*, 169, 402–412.

[15] Yoder, C.F., and Peale, S.J. (1981) *Icarus*, 47, 1-35.

[16] Peale, S.J., and Lee, M.H. (2002) *Science*, 298, 593–597.

[17] Malhotra, R. (1991) *Icarus*, 94, 399–412.

[18] Showman, A.P., and Malhotra, R. (1997) *Icarus*, 127, 93–111.

[19] Bland, M.T. et al. (2008) *Icarus*, 198, 384–399.

[20] Bland, M.T. et al. (2009) *Icarus*, 200, 207–221.

[21] Dombard, A.J. and McKinnon, W.B. (2001) *Icarus*, 154, 321–336.

[22] Schenk, P.M. et al. (2001) *Nature*, 410, 57–60.

[23] Bland, M.T. and Showman, A.P. (2007) *Icarus*, 189, 439–456.

[24] Gomes, R.S. et al. (2005) *Nature*, 435, 466–469.

[25] Radebaugh, .J. et al. (2009) *LPS XL*, abs. #1037.