DIFFERENTIATION OF LARGE OUTER SOLAR SYSTEM SATELLITES: IMPLICATIONS FOR CORE CHEMISTRY, INTERNAL STRUCTURE, AND NON-HYDROSTATIC GRAVITY. William B. McKinnon and M.T. Bland, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130 (mckinnon@wustl.edu).

Introduction: The internal structures of the major moons of the Outer Solar System, Io, Europa, Ganymede, Callisto, and Titan, can be usefully compared with those of the terrestrial planets. With sufficient heating we expect not only separation of rock from ice, but also metal from rock. The internally generated dipole magnetic field of Ganymede is perhaps the strongest evidence for this separation, but the gravity field of Io also implies a metallic core [e.g., 1]. Nevertheless, the evolutionary paths to differentiation taken (or avoided) by these worlds are quite different from those presumed to have the governed differentiation of the terrestrial planets, major asteroids like Vesta, and iron meteorite parent bodies.

Several aspects stand out. Slow accretion in gas-starved protosatellite nebulae [e.g., 2] implies that neither giant, silicate-magma-forming impacts of the terrestrial variety [3] were likely, nor were short-lived radiogenic nuclei in sufficient abundance to drive prompt differentiation (if we accept that Callisto and Titan are only partially differentiated). Rather, differentiation would have relied on late-stage impacts that could melt ice [e.g., 4], long-lived radionuclide heating, and/or in the cases of Io, Europa, and possibly Ganymede, tidal heating in mean motion resonances.

In our view, the best a priori estimate for the composition of the “rock” component near Jupiter and Saturn is solar, and it is this material that is fed into the accretion disks around Jupiter and Saturn, across the gaps the planets likely created in the solar nebula [5]. Solar composition rock implies a sulfur abundance close to the Fe-FeS eutectic (24 wt% S at GPa pressures). The rocky component of these worlds was likely highly oxidized as well, based on carbonaceous meteorite analogues, implying relatively low Mg#s (by terrestrial standards), lower amounts of Fe metal available for metallic core formation, or even oxidized Fe$_3$O$_4$ as a potential core component. The latter may be important, as an Fe-S-O melt wets silicate grains readily for $P < 3$ GPa [6,7], and thus can easily percolate downward to form a metallic core.

The amount of FeS alone available to form a metallic core may have been considerable (retaining the terrestrial nomenclature of metallic core and rocky mantle, as distinct from outer ice shell or internal ocean, unless otherwise stated). A picture emerges of large, relatively low-density cores (a far greater proportion of “light alloying elements” than in the Earth’s core), and relatively iron-rich rock mantles. Ganymede, and possibly Europa, may even retain residual solid FeS in their rock mantles, depending on their tidal heating history. These large, dominantly fluid cores imply enhanced mantle tidal deformation and heating.

Published models have claimed that the Galilean satellites are depleted in Fe compared to rock, and in the case of Ganymede, that it is either depleted or enhanced in Fe [8,9]. Obviously Ganymede cannot be both, and detailed structural models show that the Galilean satellites can be explained in terms of solar composition, once one allows for abundant sulfur and hot (liquid) cores [10,11]. While such sulfidic and oxidized core chemistries may at first blush seem exotic, they are no more intrinsically unusual than the highly reduced chemistries proposed for Mercury’s core [12].

The Titan–Callisto Challenge: The moments-of-inertia (MOIs) derived from second-degree gravity determinations for these 2 large moons, assuming hydrostatic equilibrium, are not consistent with full separation of rock from ice, let alone any internal separation of metal from rock [1,13]. Conventional pictures (i.e., [14]) of the interiors of these bodies show Callisto with a deep interior of mixed ice and rock and Titan with a large, hydrated rock core and no such mixed layer! These models should be viewed as end members, as there exist myriad ways a large accreting icy satellite may separate ice from rock (or not), and the most likely initial state involves a hydrated rocky “core” of some scale surrounded by a layer of mixed ice+rock that may or may not have the original bulk ice/rock ratio (large silicate chunks or density anomalies will sink to the center [15]).

While different internal structures can be proposed for these satellites, not all are stable from an evolutionary point-of-view. We have previously noted that a large hydrated rock core for Titan will likely largely dehydrate over Solar System history [16], rendering this explanation suspect for Titan’s large normalized MOI ($\approx 0.34$). Similarly, a 3-layer Callisto or Titan may also become too warm, with the thickness of its internal ocean setting a strict upper bound on how thick any intermediate ice+rock layer can be [17]. An example of the latter for Titan is shown in Fig. 1. In this calculation, ongoing differentiation of the mixed layer plus core dehydration force Titan to an MOI value below nominal even accounting for possible non-hydrostatic contributions (gray band, described in [13]). Either the
ice viscosity is too high or the initial extent of the mixed layer too great (the example assumes, for specificity, a rock/ice ratio equal to the bulk satellite). The presence of ammonia or methanol in the ocean would presumably make matters worse, in regard to explaining Titan’s MOI.

Complicating the MOI interpretation is the possibility of non-hydrostatic contributions to the gravity signature of these slowly rotating satellites. Such contributions may come from either strength-supported surface ice shell thickness or compositional variations or rock core irregularities [18], and will be discussed.

Figure 1. Example thermal and structural evolution of a 3-layer Titan. From a cold start (for numerical reasons), this “Titan” rapidly warms and an internal ocean forms, causing further separation of rock from ice. Thermal evolution is based on parameterized convection [19], with an ice grain size of 1 mm (and all ice phases behaving rheologically similar to ice 1). Rock liberated by melting at the base of the ocean is assumed to fall to the rock core surface, while water released by serpentine dehydration ascends to the mixed layer. In this example the ocean ultimately freezes because it contains no ammonia or methanol.

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