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Constraints on Early Solar System Dynamical Evolution from the Interior States of Ganymede and Callisto

A. C. Barr and R. M. Canup
Department of Space Studies, Southwest Research Institute, Boulder CO, USA (amy@boulder.swri.edu; robin@boulder.swri.edu/ Fax: (303) 546-9687)

Introduction. Jupiter's large ice/rock satellites Ganymede and Callisto have similar sizes and compositions, but remarkably different interior structures. *Voyager* images of the grooved terrain on Ganymede, and absence of endogenic resurfacing on Callisto, suggested that Ganymede's interior is differentiated and heavily evolved, but the Callisto is a primitive and relatively unprocessed object [e.g., 1]. Accounting for the origin of the Ganymede/Callisto dichotomy can be used to constrain key events in the early outer solar system, including the satellites' bombardment history.

Galileo data suggest that the differences between the satellites are more than skin deep. Callisto has a moment of inertia coefficient, C/MR^2=0.3549 ± 0.0042 (assuming hydrostatic equilibrium; [2,3]), intermediate between the C/MR^2 for Ganymede (0.3115; [3])) and that of a uniform-composition Callisto accounting for compression of ice-rock phases at depth (0.38; [4]). Plausible structures for Callisto's interior include some component of mixed ice/rock, suggesting that core formation in its interior is incomplete, and that the satellite has avoided global melting over its entire history.

Previous work suggests that differences in accretional environment [1, 5, 6, 10, 17, 18], thermal evolution [1,7], and/or tidal dissipation [8] can create the Ganymede/Callisto dichotomy. However, in each model, the dichotomy depends on small differences in satellite properties or rather restrictive evolution scenarios [9, 10].

We propose that for a wide range of conditions, the dichotomy can be created during an intense period of bombardment from remnants of planet formation in the outer solar system. Our conclusions depend on Callisto's interior state being well approximated by hydrostatic equilibrium. Future spacecraft data should be able to provide confirmation of this critical issue.

Outer Solar System Late Heavy Bombardment. Many of the large impact basins on the Moon have similar ages, suggesting a period of intense bombardment from known as the "late heavy bombardment" (LHB) ~700 Myr after the Moon formed. A leading theory for the origin of impactors onto Earth's Moon during the LHB suggests that the event was triggered by the early dynamical evolution of the outer planets, driven by their interaction with a disk of icy planetesimals that caused ~10^{22} g of disk material to impact the Moon [11].

During an outer solar system LHB, Ganymede receives 80x the mass of objects delivered to the Moon, some ~$6x10^{23}$ g of cometary material [11, 12,13], delivered at v_i~20 km/s [13]. The total impact energy ~10^{36} erg, ~5x higher than the energy required to melt all its ice. Callisto experiences fewer impacts at a lower characteristic velocity (v_i~15 km/s), and receives only ~1.5x the energy required to melt its ice.

Methods. Heliocentric cometary impactors that strike the moons with a characteristic velocity of a few to tens km/s [13] create a shock wave that compresses the satellite's interior, performing $P\Delta V$ work on a quasi-hemispherical region beneath the impact site. At locations where the peak shock pressure exceeds the pressure to melt ice, a buried pool of melt water and ice crystals is created. At locations where the volume fraction of melt >50% [14,15], the water/crystal slurry has a viscosity comparable to that of liquid water. In this region, concomitant rock particles >30 μm sink rapidly to the pool's base before it solidifies. At the base of the melt pool, particles consolidate into larger fragments that sink to the satellite's centre in a few thousand years. The impact-melted region is described by a sphere of radius $r_{cr}=5.06r_p(v_i/15\ \mathrm{km/s})^{0.60}$ buried at a depth $z_{cr}=2.85r_p(v_i/15\ \mathrm{km/s})^{0.47}$,

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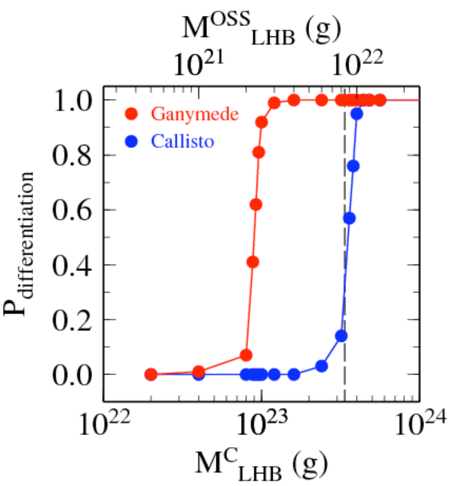
which we have determined using numerical impact simulations.

We consider an initially uniform-density satellite (ρ) containing a volume $\phi=(\rho-\rho_i)/(\rho_r-\rho_i)$ of rock with density ρ_r and ice with density ρ_i. The amount of rock added to the core from each impact is determined by adding the ϕ values from elements within the completely melted region. Rock elements added to the core displace ice/rock elements at the core's outer edge: these elements effectively switch places, mimicking the exchange of sinking coherent rock bodies with the primordial ice/rock mixture in the core. In this way, successive overlapping impacts rapidly remove rock from the satellite's outer layers, and impacts into the deep layers of primordial ice/rock mixture are the most effective at adding to the rock core.



Probability of differentiating Ganymede (red) and Callisto (blue) as a function of LHB mass at Callisto (M^C_{LHB} bottom axis) and outer solar system contribution to lunar LHB (M^{OSS}_{LHB} top axis). For $8\times10^{22} < M^C_{LHB} < 5\times10^{23}$ g, there is a >20% probability of creating the dichotomy. The dichotomy is created across the range of total impacting mass consistent with the lunar LHB, $6\pm3\pm\times10^{21}$ g (e.g., 12).

Sinking rock liberates gravitational potential energy in the form of heat in the satellite's interior. If the amount of energy liberated during the impact-induced core formation is sufficient to melt the remainder of the satellite's ice, the impact-induced differentiation begun during the LHB will drive itself to completion.

Results. If a substantial portion of the lunar LHB originated in the outer solar system, core formation in Callisto during the LHB is incomplete, but drives to completion in Ganymede. However, if the outer solar system LHB mass is higher than current theory [11] suggests, core formation in Callisto will drive itself to completion, in apparent violation of its present-day moment of inertia.

Future Spacecraft Data. Because all of the Callisto flybys were nearly equatorial and because Callisto is a slow rotator [3], it was not possible to obtain independent estimates of J_2 and C_{22} to determine whether Callisto is in hydrostatic equilibrium. The moment of inertia coefficient reported by Anderson et al., (2001) was obtained from radio tracking data under the assumption that Callisto is in hydrostatic equilibrium. This assumption may be reasonable given Callisto's size [2,3], but it should be noted that a non-hydrostatic figure (for example, the presence of mass anomalies at the surface of a rocky core) could potentially mask a higher degree of differentiation [4,16].

If Callisto is truly partially differentiated, its interior state is a powerful constraint on the timing and duration of its formation [10] and the dynamical history of the outer solar system. Spacecraft data determining whether Callisto's interior is in hydrostatic equilibrium, and the extent of differentiation in its interior could shed light on these issues.

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