ORIGIN OF THE GANYMEDE/CALLISTO DICHOTOMY BY IMPACTS DURING AN OUTER SOLAR SYSTEM LATE HEAVY BOMBARDMENT. Amy C. Barr and Robin M. Canup, Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder CO 80302, USA (amy@boulder.swri.edu; robin@boulder.swri.edu).

Introduction: Despite similar sizes and mean densities, the surfaces and interiors of Jupiter's large ice/rock satellites Ganymede and Callisto suggest that they have followed different evolutionary pathways. Ganymede shows signs of global endogenic resurfacing [1], but Callisto's surface is ancient and shows no signs of resurfacing [2]. Ganymede's low moment of inertia suggests complete ice/rock separation [3], but Callisto's higher moment of inertia suggests incomplete ice/rock separation in its interior [3,4]. Previous work suggests that differences in accretion environment [e.g., 5,6,7,8,9,10], thermal evolution [5, 10], and/or tidal dissipation [11] can create the Ganymede/Callisto dichotomy. In each model, the dichotomy depends on small differences in satellite properties or restrictive evolution scenarios [9,12].

Here, we construct geophysical models of impact-induced ice/rock separation to show that the Ganymede/Callisto dichotomy can be created during an outer solar system "late heavy bombardment" (LHB).

Outer Solar System Late Heavy Bombardment: Many of the large impact basins on Earth's moon have similar ages, suggesting a period of intense bombardment known as the "late heavy bombardment" (LHB), ~700 Myr after the Moon formed. A leading theory for the origin of LHB impactors, the so-called *Nice* model, suggests that the event was triggered by the early dynamical evolution of the outer solar planets, driven by their interaction with a disk of icy planetesimals. If the planetesimal disk is initially ~35$M_{\oplus}$ (earth-masses), and is whittled down to ~20$M_{\oplus}$ at the time of the LHB, ~10^{22} g of icy objects will impact the Moon [13, 14], comparable to the lunar LHB mass estimated from the cratering record [13].

During an outer solar system LHB, Ganymede receives 80x the mass of objects delivered to the Moon, some ~6x10^{23} g of cometary material [13,14,15], delivered at a characteristic impact velocity v_i=20 km/s. Callisto experiences fewer impacts at a lower v_i=15 km/s.

Methods: *Impacts*. A heliocentric cometary impactor that strikes a moon with a characteristic velocity of ~ tens of km/s creates a shock wave that compresses the satellite's interior, performing PΔV 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 exceeds 50% [16, 17, 18], 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.

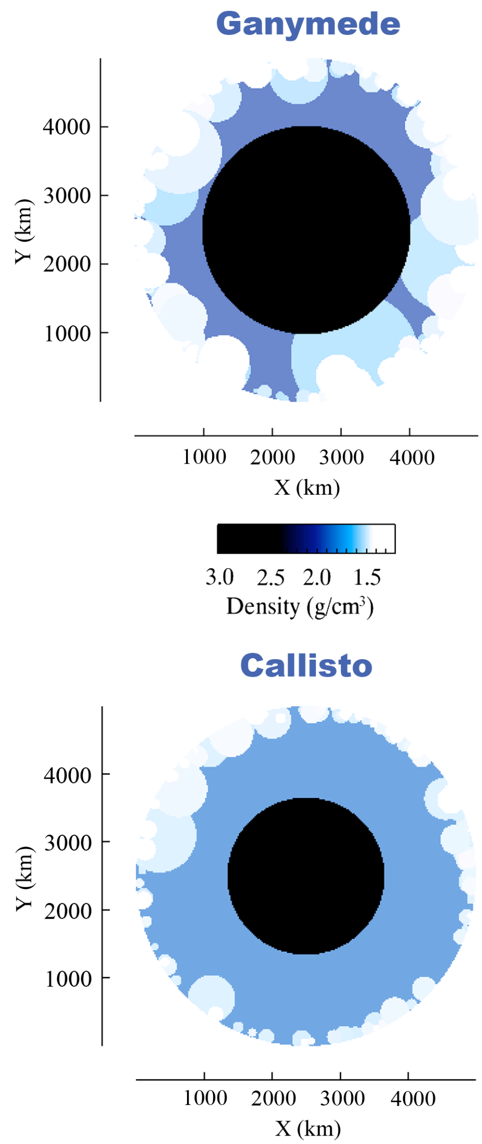

Figure 1. Heterogeneous density structures inside Ganymede (top) and Callisto (bottom) after the LHB. Colors indicate density.

At the base of the melt pool, particles consolidate into larger fragments that sink to the satellite's center in a few thousand years [19]. We performed simulations of ice/ice impacts using the CTH hydrocode [20] and the semi-analytic equation of state for water ice (ANEOS) [21] with parameters appropriate for water ice after Turtle & Pierazzo [2001; 22]. We find that the impact-melted region can be described by a sphere of radius

r_{cr}=5.06r_p(v_i/15 km/s)$^{0.60}$ buried at depth z_{cr}=2.85r_p(v_i/15 km/s)$^{0.47}$, where r_p is the impactor radius.

Core Formation. Model satellites are represented by a 3D Cartesian sphere containing an initially volume $\phi=(\rho-\rho_i)/(\rho_r-\rho_i)$ of rock with density ρ_r and ice with density ρ_i. The initial rock volume fraction is ϕ=0.44 for Callisto and ϕ=0.52 for Ganymede, assuming a nominal ρ_i=1.4 g/cm^3 and ρ_r=3.0 g/cm^3 [19]. The size, velocity, location, and angle of the few thousand impactors onto each satellite are selected using a Monte Carlo approach. The impactor radii are drawn from a population similar to Jupiter's Trojan asteroids [23, 24], which are thought to be populated by an outer solar system LHB [24]. The most likely impactor radius is 30 km.

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. 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. Successive overlapping impacts rapidly remove rock from the satellites' outer layers, and impacts into the deep layers of primordial ice/rock are most effective at adding to the core.

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, differentiation will drive itself to completion [BC10]. Figure 1 illustrates the heterogeneous density structures in Ganymede and Callisto after the LHB.

Results: Figure 2 illustrates the probability of differentiating Ganymede and Callisto during an outer solar system late heavy bombardment as a function of the cometary disk mass at the time of the LHB (M_D). The probability of differentiation for each M_D is determined by simulating core formation with 100 different impactor populations. For the M_D= 20$M_\oplus$ disk that creates a lunar LHB of the observed magnitude and places the outer planets on their correct orbits [14, 25], we find that Ganymede is differentiated, but Callisto is not.

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. Our results suggest that in the context of the *Nice* model, the Ganymede/Callisto dichotomy occurs as a natural result of dynamical sculpting of the outer solar system.

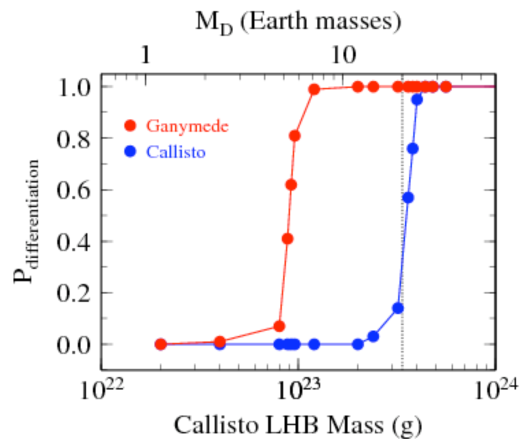

Figure 2. Results of Monte Carlo simulations constraining the probability of triggering runaway differentiation in Ganymede and Callisto during the LHB. Vertical line shows M_D=20$M_\oplus$ predicted by the *Nice* model.

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