CONSTRAINTS ON AN OUTER SOLAR SYSTEM LATE HEAVY BOMBARDMENT FROM CALLISTO'S INTERIOR STATE.
A. C. Barr and R. M. Canup, Department of Space Studies, Southwest Research Institute, Boulder CO 80302 (amy@boulder.swri.edu; robin@boulder.swri.edu).

Introduction: One difficulty in explaining the lunar late heavy bombardment (LHB) lies in identifying a source of impactors that survives at ~3.8 to 4 Gyr, so long after planet formation [1,2]. A leading theory is that the LHB was triggered by events in the outer solar system [3,4]. Any model that invokes an outer solar system source for the lunar LHB will also produce an intense bombardment on the Galilean satellites because their effective "target areas" are larger than that of Earth's moon due to strong gravitational focusing by Jupiter [3].

During an outer solar system LHB, Jupiter's outermost regular satellite Callisto would receive an impacting mass some ~ 40 times larger than Earth's moon [3]. The mass would be delivered in the form of a few thousand icy impactors with radii r_p~10 to a few hundreds of km. The objects would come from heliocentric orbit and have characteristic impact velocities v_i~ 15 km/s [5]. If outer solar system impactors produced the entire lunar LHB, the bombardment of Callisto would deliver about twice the amount of energy required to melt all of Callisto's ice.

Plausible interior structures for Callisto based on *Galileo* radio tracking data include some component of mixed ice/rock in its interior, assuming hydrostatic equilibrium [6]. This implies that Callisto has never experienced widespread melting in its interior, including during its formation, long-term thermal evolution, and a possible outer solar system LHB. Thus, limits on the size of a rocky core in Callisto based on its moment of inertia constant can be used to constrain the contribution of outer solar system impactors to the lunar LHB.

Impact-Induced Core Formation: Impacts with v_i > 3 km/s onto a surface composed of a mixture of ice and rock will create pools of H_2O melt. At locations where the peak shock pressure is high enough to melt ice, rock suspended in the ice will sink to the base of the melt pool and consolidate into a large rock body that can sink rapidly to the satellite's center [*cf.* 7].

We have constructed a simple model of core formation due to repeated impacts of icy objects with a homogeneous ice/rock callisto. Callisto begins as a homogeneous ice/rock sphere with mean density ρ=1.834 g/cm^3 [8] composed of rock with density ρ_r=3.0 g/cm^3 and ice with a representative density ρ_i=1.4 g/cm^3 to account for solid-solid phase transitions and compression at depth. With this choice of ice and rock density, the model satellite's rock mass fraction, m_r=0.44, is consistent with more physically realistic models of Callisto's interior [9], and yields a volume fraction of rock, $\phi=(\rho-\rho_i)/(\rho_r-\rho_i)=0.27$.

Callisto's interior is represented by ~ 10^7 cubical elements, each 20 km on a side. Latitude, longitude, v_i, projectile radius (r_p), and impact angle for each of several hundred to thousand impact events are selected using a Monte Carlo approach. Impact velocities are Rayleigh-distributed with mean v_i=15 km/s [5]. The effect of impact angle is taken into account using an equivalent vertical impact scaling [10].

Size of Melted Region. To constrain the shape and depth of the region in Callisto melted by each impact, we perform simulations of ice/ice impacts using the Eulerian hydrocode CTH [11]. We use CTH with the equation of state ANEOS [12], with parameters for water ice from [13]. Following the methods of [14], we use stationary tracers to determine how the peak shock pressure in the target (P_{sh}) during a vertical impact decays as a function of distance from the impact point. The radius of the completely melted region is defined as the location where P_{sh} > 3.25 GPa, the pressure for shock-induced melting in ice (mid-way between values for 120 K and 260 K [15]). The melted region is roughly spherical with radius r_{cm} and depth of burial z_{cm}, where $(r_{cm}/r_p)=8.85\,(v_i/15\text{ km/s})^{0.95}$ and $(z_{cm}/r_p)=5.04\,(v_i/15\text{ km/s})^{0.75}$ for 7 km/s < v_i < 40 km/s.

Core Formation. The amount of rock added to Callisto's 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. The core is assumed to grow in a radially symmetric fashion. Displaced ice/rock core elements are mixed with the ϕ=0 elements created in the impact crater, in a crude approximation of isostatic adjustment post-impact. In this way, successive overlapping impacts rapidly remove rock from Callisto's outer layers, and impacts into the deep layers of primordial ice/rock mixture are the most effective at adding to the rock core.

Criteria for Success. If enough potential energy is released by partial differentiation to melt Callisto's ice, the impact-induced differentiation begun during the LHB will drive itself to completion. We calculate the change in gravitational potential energy (ΔE_{diff}) between the initially homogeneous-density satellite and a two-layered structure with core density ρ_r and radius determined from our simulations, and outer mantle density ρ_m [16]. Runaway differentiation occurs if $\Delta E_{diff} > L_i(1-m_r)M$ where M is Callisto's mass and L_i=3.3x10^9 erg/g is the ice latent heat. This places severe limits on the extent of differentiation.

Alternatively, if Callisto can remove the energy of differentiation deposited during the LHB, perhaps by vigorous convection, a successful model could have

$C/MR^2 \geq 0.3507$, the lower limit permitted by the *Galileo* radio tracking data [8]. Moment of inertia values for our model callisto are calculated using a two-layered model wherein the core has density ρ_r and radius determined from our simulations, and the mantle density is obtained by averaging final mantle ϕ values.

The Nice Model LHB: One leading theory for the source of the LHB impactors is the so-called "Nice model", which proposes that Jupiter, Saturn, Uranus, and Neptune formed in closely spaced orbits. Subsequent gravitational interactions between themselves and a massive disk of planetesimals caused the planets' orbits to migrate, and Jupiter and Saturn to cross a mutual mean-motion resonance. This causes the 4-planet configuration to destabilize, and ~ 10^{22} g of planetesimal disk material to hit Earth's moon, comparable to the lunar LHB [4].

The Nice model predicts that the size distribution of small objects hitting the Moon and by extension, Callisto, is similar to the population of Jupiter's Trojan asteroids ($dN_{sm}/dr_p \sim r_p^{-3}$), and that large objects follow a size distribution similar to the dynamically cold Kuiper Belt ($dN_{bg}/dr_p \sim r_p^{-6.5}$ for $r_p > 50$ km) [17].

Results: The top panel of Figure 1 illustrates the probability that Callisto remains undifferentiated after an outer solar system LHB as a function of the Callisto LHB mass and the outer solar system contribution to the lunar LHB. A Nice-model LHB delivering $(8.4\pm0.3)\text{x}10^{21}$ g of material from the outer solar system to the moon, and 40 times that to Callisto (3 to $4\text{x}10^{23}$ g) will trigger runaway differentiation. For Callisto to avoid differentiating, the LHB mass must be less than $4\text{x}10^{22}$ g, a factor of 10 less than implied by the Nice model (blue vertical lines). This implies that the contribution to the lunar LHB from the outer solar system is constrained to < 10^{21} g, or ~15 to 20%, assuming a total LHB mass ~ $6\text{x}10^{21}$ g [3].

Making the approximation that Callisto can remove ΔE_{diff}, which is liberated in its deep interior, a successful model must satisfy only Callisto's present-day C/MR^2 (Figure 1, bottom), which permits more differentiation. However, this seems unrealistic, given that ΔE_{diff} would have to be removed by convection and conduction over geologically long time scales. The C/MR^2 constraint permits a higher Callisto LHB mass, ~10^{23} g, corresponding to an outer solar system contribution to the lunar LHB of ~$2\text{x}10^{21}$ g, or 30%.

If Callisto is truly partially differentiated, its interior state is a powerful constraint on the timing and duration of its formation [18] 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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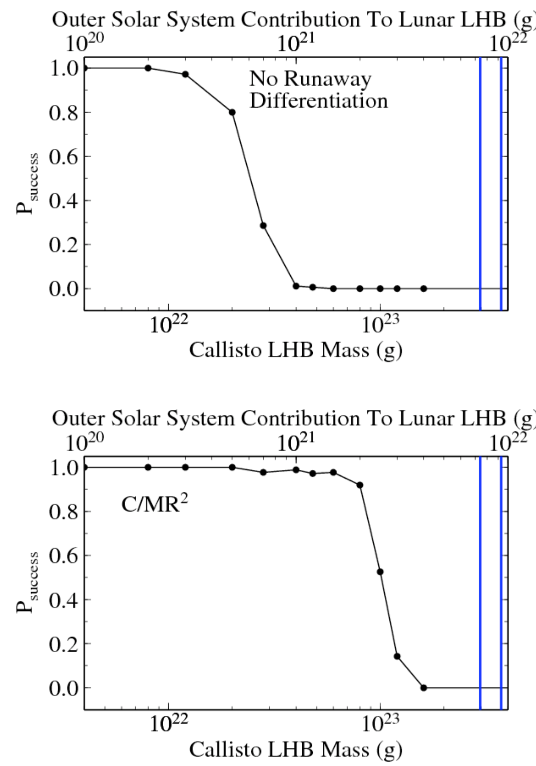

Figure 1. (top) Probability that Callisto avoids runaway differentiation during an outer solar system LHB as a function of total LHB mass at Callisto (bottom axis) and outer solar system contribution to lunar LHB mass (upper axis), a factor of 1/40 lower than the Callisto LHB mass. Blue vertical bars indicate the range of LHB masses predicted by the Nice model. (bottom) Probability that model callistos have a moment of inertia constant (C/MR^2) consistent with the present-day *Galileo* value. Applying the less-stringent C/MR^2 constraint makes the probably unrealistic assumption that Callisto can efficiently remove energy deposited in its deep interior during impact-induced core formation and prevent runaway differentiation.