CONSTRAINTS ON GAS GIANT SATELLITE FORMATION FROM THE INTERIOR STATES OF PARTIALLY DIFFERENTIATED SATELLITES. Amy C. Barr and Robin M. Canup. Department of Space Studies, Southwest Research Institute, Boulder, CO (1050 Walnut St. Suite 300 Boulder CO 80302; amy@boulder.swri.edu)

Motivation: Geological characterization and estimates of moments of inertia from spacecraft radio tracking data suggest that Jupiter's outermost large satellite Callisto and Saturn's mid-sized icy moon Rhea may be partially differentiated [1,2,3,4]. If part of the interiors of Callisto and Rhea consist of a homogeneous ice/rock mixture, they must have avoided widespread melting during their formation and subsequent evolution. This requires that Callisto formed slowly to allow its accretional energy to be radiated away between successive impacts. A slow accretion is implicated for Rhea for many conditions as well. Also, both bodies must form late enough in solar system history to avoid internal melting from short-lived radioisotope (SLRI) heating. If Callisto and Rhea formed in the final stages of giant planet growth at the end of the lifetime of the solar nebula [5,6], constraints on the endpoint of their formation can constrain the timing of giant planet formation and nebular dispersal in our solar system.

Prior Work: A rough estimate of the energy liberated within a satellite during its formation is given by its gravitational binding energy per unit mass, E_a~3/5 GM_s/R_s where M_s and R_s are the satellite mass and radius, G is the gravitational constant, and L is the latent heat of fusion of water ice. Callisto's binding energy is comparable to the latent heat of water ice (L), E_a~$3L$, suggesting that its icy component should melt during formation if most of its accretional heat is retained. Rhea is more likely to avoid melting because E_a~(1/3)L, but E_a is sufficient to raise its temperature by ~100 K, so SLRI heating and accretional energy may be able to cause melting.

Existing models of the thermal evolution of growing icy satellites rely on a simple approach wherein a poorly constrained fraction "h" of accretional energy deposited by impacts is retained and used to heat the satellite [7,8]. For h < 0.1, corresponding to small impactors that deposit energy close to the satellites' surfaces, it is possible to form unmelted callistos, however, it has not been known whether this value is realistic [Stevenson1986]. If Callisto accretes in an optically thin disk and avoids accreting a substantial gaseous envelope so its surface can cool by radiation, it can remain unmelted if formed slowly ($\tau_{accc} > 10^5$ yr) [8]. Aluminum-26 heating alone provides enough energy to melt the ice in Callisto unless it formed later than 2.6 to 3 Myr after CAI condensation [9].

Squyres et al. [1988] [10] found that Rhea can avoid melting during relatively rapid formation in a minimum-mass subnebula around Saturn for $0.2 < h < 0.6$. However, Squyres et al., [1988] did not include SLRI heating.

We use estimates of the temperature rise associated with radiogenic and accretional heating, coupled with limits on satellite melting based on their measured moments of inertia to constrain the timing of formation of Callisto and Rhea relative to the origin of the calcium-aluminum-rich inclusions (CAI's) as a function of the accretion time scale and the protosatellite disk temperature (T_d).

Formation Environment: The ranges of accretion time scales and protosatellite disk temperatures we consider are motivated by two different scenarios for conditions in the jovian and saturnian protosatellite disks: the traditional minimum-mass subnebula model [e.g., 11,12] and the slow inflow/gas-starved disk model [5,6]. Historically, satellite formation models focus on the evolution of the MMSN, wherein the masses of the currently observed satellites are combined with gas to create a massive solar-composition disk around the parent planet. MMSN models predict dense, gas-rich, and warm protosatellite disks leading to rapid formation of satellites with interiors heated close to, or well above their melting points [5,8,10,13]. An alternative approach [5] considers satellite growth in a "gas-starved" disk supplied by the slow inflow of gas and ≤1 meter-sized rock and ice particles from solar to planetary orbit. Simulations of satellite accretion in the CW scenario show that during gas inflow, multiple generations of satellites are created with all but the last colliding with the growing planet [6]. The final Galilean and saturnian satellites form during the waning stages of Jupiter and Saturn's gas accretion [5,6], implying that the observed satellites formed in a disk with a much lower gas density than the MMSN. In the CW model, the satellites also accrete very slowly, at a rate controlled by the delivery rate of ice/rock solids to the disk at the end of giant planet formation.

A lower limit on the temperatures in the protosatellite disks at Jupiter and Saturn are the solar nebula temperatures at the parent planets' locations, T_d~T_{neb}~100 – 150 K at Jupiter, and T_{neb}~90 K at Saturn [14]. The requirement for ice stability (T_d < 200 K) provides an upper limit on protosatellite disk temperatures during the formation of both satellites. In a MMSN, Rhea and Callisto form in τ_{acc} ~O(10^3) yr [5,10,15]. In the CW model, satellite formation time scales and protosatellite disk temperatures are controlled by the rate of delivery of ice/rock to the protsatellite disk, τ_{acc} ~ 0.1 – 10 Myr [16]. The satellites must also finish forming before solar nebula dispersal ~O(1-10) Myr after CAI's [17].

Methods: Accretional temperature profiles for a growing satellite are calculated by balancing radiation from its surface, heating of impacted material from its initial temperature (which we assume has the same temperature as the disk, T_d) to the satellite's surface temperature (T), accretional heating, and radiogenic heating,

$$\rho_s C_p (T - T_d) \frac{dr}{dt} = \frac{u_i^2}{2} \frac{1}{4\pi r^2} \frac{dM}{dt} - \sigma_{SB}(T^4 - T_d^4), \quad (1)$$

with Stefan-Boltzmann constant σ_{SB}, impact velocity u_i, specific heat C_p=1700 J/kg, radial coordinate within the satellite r, mass accretion rate $dM/dt=M_{s,f}/\tau_{acc}$ where $M_{s,f}$ is the final satellite mass and τ_{acc} is the accretion time scale, chondritic heating rate q_r, and satellite rock mass fraction $m_r=(\rho_r(\rho_s-\rho_i))/(\rho_s(\rho_r-\rho_i))$ where ρ_i=1000 kg/m^3 and ρ_r=3000 kg/m^3 is a representative rock density. After material at a radius r is accreted, radiogenic heating increases its temperature by ΔT_r,

$$\Delta T_r = \frac{1}{\rho_s C_p} \int_{t_f}^{\infty} q_{26}(t)dt = \frac{q_{26}(0)}{\lambda_{26}} \exp(-\lambda_{26} t_f), \quad (2)$$

where $q_{26}(0)$~ 1.63x10^{-7} W/kg (using $^{26}Al/^{27}Al$= 5.25x10^{-5} from Bizzarro *et al.,* (2004) [18] and total Al abundance from Lodders (2003) [19]) is the radiogenic heating rate from ^{26}Al at t=0, the time of CAI condensation, and λ_{26}=9.68x10^{-7} yr^{-1} is the decay constant.

By using eq. (1) we have implicitly assumed that all accretional energy is delivered by small impactors and is deposited close to the surface where it is radiatively cooled (*i.e.*, h ~ 0). If Callisto and Rhea form in a gas-starved disk, the small rock/ice particles flowing onto the protosatellite disk likely do not grow into large objects before being accreted onto growing satellites: we estimate the characteristic sizes of objects hitting Callisto ~O(1 km) and ~O(1 m) for Rhea [16]. If the satellites formed from large impactors and/or more heat was deposited at depth, it would make melting more likely than our estimates here.

The time at which a layer accretes (t_f) is,

$$t_f = t_{start} + \frac{4}{3}\frac{1}{F_g}\left(\frac{\rho_s r}{\sigma}\right)\Omega^{-1}, \quad (3)$$

where t_{start} is the time at which the satellite starts accreting relative to CAI's, σ is the surface mass density of disk solids, Ω is the orbital frequency, and $F_g=1+(v_{esc}/v_\infty)^2$ is the gravitational focusing factor, a function of the characteristic relative velocity of accreting material, v_∞, and satellite escape velocity $v_{esc}=(2GM(t)/r(t))^{1/2}$. We assume F_g=5, so that $u_i(t)$ ~ 1.1$v_{esc}(t)$.

To assess whether a given set of T_d, τ_{acc}, and t_{start} values leads to an interior structure consistent with the satellites' measured moments of inertia, we compare accretional temperature profiles to the pressure-dependent melting point of water ice.

Results: *Rhea.* If partially differentiated, Rhea must have finished accreting no earlier than 1.8 Myr after CAI condensation to avoid early melting. For (τ_{acc} < 10^3 yr), Rhea's formation must have been delayed until at least 2.3 Myr after CAI's if T_d~90 K [14], and if T_d~120 K, accretion must be delayed until 2.7 Myr after CAI's. For T_d > 180K, rapid accretion with τ_{acc} ≤ 10^3 yr leads to excessive melting compared to the Anderson and Schubert [3] and Iess et al. constraints [4] no matter how late Rhea forms.

Callisto. If Callisto was assembled from small planetesimals that deposit their impact energy close to the surface where it can be lost from radiative cooling, it can avoid melting if it formed in τ_{acc} > 0.7 Myr with T_d=130 K. Considering both ^{26}Al and accretional heating, Callisto must finish forming no earlier than 4 Myr after CAI's if T_d~100 K, close to the temperature of the solar nebula at Jupiter's location. For a nominal T_d=130 K, Callisto must finish accreting *no earlier* than 5 Myr after CAI's. The same accretion start times and time scales that give undifferentiated callistos can be consistent with a primordial Ganymede/Callisto dichotomy for some combinations of τ_{acc} and τ_{start}. This is because Ganymede is more massive and rock-rich, and it may have also formed in warmer disk conditions.

In the context of the CW satellite formation hypothesis, our results suggest that gas inflow to Jupiter and Saturn ended *no earlier* than times comparable to the average nebular lifetimes inferred from circumstellar disks, ~3 Myr [17].

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