FORMATION OF THE SATURNIAN SATELLITES: CONSTRAINTS FROM RHEA'S UNDIFFERENTIATED STATE. Amy C. Barr and Robin M. Canup, Department of Space Studies, Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder CO 80302 (amy@boulder.swri.edu).

Introduction: *Cassini* flybys of Saturn's satellite Rhea (R_s=765 km, ρ_s=1233 kg/m^3 (Anderson & Schubert 2007)) have constrained its moment of inertia factor in independent analyses, C/MR^2=0.3721±0.0036 (Iess *et al.,* 2007) or 0.3911±0.0045 (Anderson & Schubert 2007). Both analyses suggest that Rhea is in hydrostatic equilibrium.

For Rhea to remain undifferentiated at present, it must have avoided widespread melting during its formation, when accretional energy and possibly decay of ^{26}Al delivered an initial burst of heat to its interior. We use estimates of the temperature rise associated with ^{26}Al and accretional heating to constrain the timing of Rhea's formation relative to the origin of CAI's as a function of Rhea's accretion time scale and the protosatellite disk temperature.

Our study has three goals: 1) To begin to assess whether Rhea's current state is consistent with its formation in a "gas-starved" disk as described by Canup & Ward (2002, 2006); 2) To constrain the age of Saturn's satellites, and by extension, the Saturn system; 3) To place an upper limit on the amount of ^{26}Al present to drive early geologic activity in the Saturn system.

Satellite Formation: Physically motivated models of Jupiter's growth (*e.g.,* Lubow *et al.,* 1999, Papaloizou & Nelson 2005), Ganymede and Callisto's ice-rich compositions, and of Callisto's interior state led Canup & Ward (2002) to suggest that the Galilean satellites, and by extension, the Saturnian regular satellites (Canup & Ward 2006) formed in a "gas-starved" disk supplied by a slow inflow of solid rock and ice from solar orbit.

In this scenario, gas from the solar nebula and rock-ice particles < 1 m in radius entrained in the gas inflow to the protosatellite disk. Gas flowing onto the disk achieves circumplanetary orbit and spreads viscously both outward and inward onto the growing planet. Rock-ice particles delivered to the disk also achieve circumplanetary orbit where they quickly accumulate into objects large enough to become decoupled from the gas, ultimately accreting into satellites. As the disk is continuously supplied with new material from solar orbit, the gas density in the disk achieves a quasi-steady state, but solids become concentrated in the disk over time.

In the Canup & Ward model, satellite growth rates are controlled by the rate of delivery of solids to planetary orbit. Estimates for Rhea's accretion time scale are 10^5 to 10^6 yr (Canup & Ward 2002; Barr & Canup 2007), perhaps more consistent with the partially differentiated state of Rhea than prior work (Squyres et al., 1988) where Rhea accreted 10^3 yr in a minimum-mass subnebula (MMSN) around Saturn. Although the slow formation of Rhea predicted by Canup & Ward hypothesis strongly suggests it can remain unmelted during formation, this has yet to be shown explicitly.

^{26}Al & The Timing of Satellite Formation: It has recently been suggested that heating from short-lived radioisotopes (SLRI's) is required to "kick start" activity in the interiors of Iapetus and Enceladus (*e.g.,* Castillo *et al.,* 2005, 2006, Castillo-Rogez *et al.,* 2007, Matson *et al.,* 2007). If these materials were present in Iapetus and Enceladus, they would have been present in Rhea's interior as well because all three satellites presumably formed at the same time. However, combined accretional and ^{26}Al heating may provide enough energy to melt Rhea, which limits the amount of radiogenic heating that could have occurred. Because the ^{26}Al heat source is strongly time-dependent, avoiding ^{26}Al meltdown requires that Rhea form relatively late after CAI condensation (*cf.* similar arguments for Callisto by McKinnon 2006). It is not clear that the presence of SLRI's in Enceladus and Iapetus is consistent with Rhea's state.

Accretional Temperature Profiles: Accretional temperature profiles for a growing Rhea 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 surface temperature (T), accretional heating, and radiogenic heating,

$$\sigma_{SB}(T^4 - T_d^4) + \rho_s C_p (T - T_d)\frac{dr}{dt} = \frac{1}{2}\frac{\dot{M}u_i^2}{4\pi r^2} + \frac{r q_r(t_f) m_r}{3}, \quad (1)$$

with Stefan-Boltzmann constant σ_{SB}, specific heat C_p=1700 J/kg, radial coordinate within Rhea r, mass accretion rate $\dot{M}=M_{s,f}/\tau_{acc}$ 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) and total Al abundance from Lodders (2003)) 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 thus deposited close to the surface where it is radiatively cooled. If more heat was deposited at depth, it would make melting more likely. By making this assumption we search for the coldest possible protorheas, which are more likely to be consistent with its C/MR^2 than cases involving accretion from large objects. We ignore solid-state heat transfer by conduction and convection.

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

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

where t_{start} is the time at which Rhea starts accreting relative to CAI's, σ is the surface mass density of disk solids, Ω is Rhea's 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 $v_{esc}=(2GM/R)^{1/2}$. We assume $F_g=5$.

To avoid melting during formation, we adopt the simple criterion that Rhea's temperature must be less than the pressure-dependent melting temperature of water ice, which ranges from 273 K at its surface to 260 K at its central pressure of 124 MPa.

Results: Key controls on Rhea's accretional temperature profiles are t_{start}, τ_{acc}, and the disk temperature T_d. We consider the disk temperature to be a free parameter, within limits based on the requirement that solid ice be present at the orbit of Rhea during its accretion (T_d<273 K), and $T_d \geq 90$ K, which is the predicted solar nebula temperature at Saturn's location (Garaud and Lin 2007)).

If Rhea accretes too early in solar system history, its interior will be melted by ^{26}Al decay while it forms. If Rhea forms too quickly, accretional energy will melt its outermost layers. For a given nebular environment (described by T_d and τ_{acc}), there exists a critical value of t_{start}, t_{crit}, where for $t_{start} < t_{crit}$, Rhea experiences melting during accretion, and for $t_{start} > t_{crit}$, Rhea remains unmelted during accretion. Rhea then finishes accreting at time $t_{end,c}=t_{crit}+\tau_{acc}$. Figure 1 summarizes how $t_{end,c}$ varies as a function of T_d and τ_{acc}.

Conclusions: Our model assumes maximally efficient radiative cooling of the satellite; as a result, our calculations provide an upper limit on the age of the Saturnian inner satellites as a function of satellite origin conditions.

1) Is Rhea's Interior State Consistent With Its Formation In a Gas-Starved Disk? Rhea can remain unmelted during accretion if it formed in conditions consistent with the satellite formation hypothesis of Canup & Ward (2002), where $10^5 < \tau_{acc} < 10^6$ yr, provided it finished forming more than $t_{end,c}$>2 Myr after CAI's. Solutions in which Rhea avoids melting exist across the entire range 90 K< T_d < 273 K for $\tau_{acc} > 10^5$ yr. In the context of the Canup & Ward model, the implied ages suggest that gas inflow to Saturn ceased *no earlier* than times comparable to the average nebular lifetimes inferred from circumstellar disks.

2) What is the Upper Limit on the Age of the Saturn System? Rhea must have finished accreting no earlier than 2 Myr after CAI's to avoid early melting. In the case of rapid formation, ($\tau_{acc} \leq 10^3$ yr) Rhea's formation must have been delayed until at least 3.25 Myr after CAI's for T_d=90 K, and for at least 4.5 Myr for T_d=120 K. For $\tau_{acc} \leq 10^3$ yr and T_d>130 K, melting is predicted for all formation times.

3) Can ^{26}Al Kick-Start Activity in Saturn's Satellites? To avoid ^{26}Al meltdown in Rhea, it is necessary for it to finish accretion *no earlier* than 2 Myr after CAI's, at which point the ^{26}Al heating rate has decreased to 1/10th its initial value. This places an upper limit on the role of ^{26}Al in the early Saturn system.

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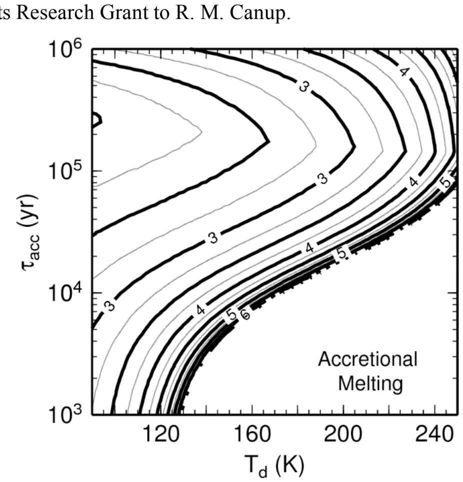

Figure 1. Contours of $t_{end,c}$ required to prevent Rhea from melting during its formation as a function of τ_{acc} and T_d. Rhea must finish accreting between 2.1 and 7 Myr for the range of τ_{acc} and T_d we consider. Fast accretion and high T_d (as suggested foor a MMSN) leads to near-surface melting due to impact energy. Slow growth (0.1 to 1 Myr) that ends > 2 Myr after CAI's is consistent with its present interior state.