MODIFICATION OF THE ROCK CONTENT OF THE INNER SATURNIAN SATELLITES BY AN OUTER SOLAR SYSTEM LHB. R. M. Canup, Planetary Science Directorate, Southwest Research Institute (1050 Walnut Street, Suite 300; Boulder, CO 80302; robin@boulder.swri.edu).

Introduction: A recent model for the origin of Saturn's rings predicts that Mimas, Enceladus and Tethys were spawned from a massive primordial ring as it viscously expanded [1]. This implies that these three inner moons (or their progenitors) were initially primarily ice. While as a group these moons contain ~ 90% ice, they do contain rock, particularly Enceladus (Tables 1 and 2). Here I consider how heliocentric bombardment might have altered the rock content of the inner Saturnian moons.

Outer solar system LHB: In the "Nice" model [2], the giant planets begin in a compact orbital configuration. Their orbits migrate due to dynamical interactions with a planetesimal disk of initial mass M_{disk}. A period of dynamical instability ensues, during which planetesimals are scattered across the solar system and become a population of impactors that can, e.g., account for the so-called lunar "late heavy bombardment", or LHB [3]. Forming a planetary system like ours appears most likely for $35M_\oplus \le M_{disk} \le 70M_\oplus$ [2,4], and the total mass of scattered planetesimals scales roughly with M_{disk}.

While I use specific predictions of the Nice model, the existence of an enhanced bombardment period in the outer solar system—an "OSS-LHB"—applies more generally. The structure of the Kuiper Belt appears to require that Neptune migrated outward via planetesimal scattering [5], and this implies both an initially more compact giant planet configuration and a planetesimal disk containing between 10 and $100M_\oplus$ [6-7]. The interaction of the giant planets with such a massive disk would have likely produced an enhanced bombardment period even if the details of the evolution differed from that of the Nice model.

Inner Saturnian moons: Table 1 lists properties of the inner satellites including estimated ranges for the satellite rock mass fractions (x_r). Table 2 lists the corresponding total rock mass (m_r) in each satellite. Satellite origin models generally predict that in regions cold enough for ice, satellites should have roughly half rock, half ice. While stochastic events could lead to some variation, it is difficult to explain, e.g., the stark difference in rock content between neighboring Tethys ($x_r \le 0.06$) and Dione ($x_r \sim 0.5$): while the masses of these satellites vary by less than a factor of two, their rock contents vary by more than factor of ten.

Object	a/R_S	Mass (10^{22} g)	ρ (g/cm^3)	x_r
Mimas	3.09	3.75	1.15	0.17 – 0.28
Enceladus	3.95	10.8	1.61	0.52 – 0.61
Tethys	4.89	61.7	0.97	0 – 0.06
Dione	6.26	105	1.48	0.44 – 0.54
Rhea	8.74	230	1.23	0.25 – 0.35

Table 1. Properties of Saturn's inner moons. Orbital radius (a) is scaled by Saturn's radius (R_S), ρ is bulk density, and x_r is the estimated rock mass fraction. Endogenic activity would have removed ice relative to rock due to its higher volatility, so that Enceladus may have initially had a lower density and a higher fractional ice content.

Delivery of rock by an OSS-LHB: Heliocentric impactors would contain both ice and rock. Table 2 gives impact probabilities onto each satellite [8], from which I estimate the total impacting mass as a function of planetesimal disk mass, M_{disk}, assuming that 1.4×10^{22} g impacts the Moon for $M_{disk} = 35M_\oplus$ [3]. The last column is the total rock mass that would impact each satellite during an OSS-LHB ($M_{r,LHB}$) for $35M_\oplus < M_{disk} < 70M_\oplus$, assuming impactors contain 50% rock.

Satellite	m_r (10^{22} g)	P_I (10^{-6})	$M_{r,LHB}$ (10^{22} g)
Mimas	0.64 – 1.1	1.7	0.79 – 1.6
Enceladus	5.6 – 6.6	2.2	1.0 – 2.1
Tethys	0 – 3.7	7.9	3.7 – 7.4
M+E+T:	6.2 – 11.4		5.5 – 11.1
Dione	46 – 57	7.1	3.3 – 6.6
Rhea	58 – 81	9.6	4.5 – 9.0
D+R:	104 – 138		7.8 – 15.6

Table 2. The total rock mass in each satellite (m_r), comet impact probability relative to that of Jupiter, P_I [8], and total rock mass impacting the satellite during an OSS-LHB ($M_{r,LHB}$), for disks with $35M_\oplus < M_{disk} < 70M_\oplus$. Cumulative totals for m_r and $M_{r,LHB}$ are shown for the inner (M+E+T) and outer satellites (D+R) in red and blue, respectively.

For Dione and Rhea, $M_{r,LHB} << m_r$, and an OSS-LHB would not substantially alter their compositions. However Mimas, Enceladus and Tethys receive a proportionally much larger rock mass. *Notably, the estimated total rock mass delivered by OSS-LHB impactors to these inner three satellites is comparable to their current total rock content (Table 2, red).*

Fate of impacting rock: Where does rock impacting each moon ultimately accrete? Due to gravitational focusing by Saturn, the impact velocity (v_i) greatly exceeds the satellite's escape velocity (v_{esc}). The impactor material will have initial ejection velocities (v_{ej}) within a factor of several of v_i, and will be shock heated to temperatures ~ 2000 to 8000°K and a primarily melt-vapor state for all but the most highly oblique impacts, e.g. [9-10]. Fig. 1 shows a simulation of an OSS-LHB impact onto Tethys. Essentially all of the impactor (~ 10^{20} g) escapes the satellite, while the satellite retains nearly all its mass. After 10 hr, ~ 50% of escaping particles have $v_{ej} \geq 4$ km s^{-1}. Tethys' orbital velocity is v_{orb} ~ 12 km s^{-1}, so that v_{ej} ~ 4 km s^{-1} corresponds to an initial ejecta eccentricity $e \sim v_{ej}/v_{orb} \sim 0.3$.

Ejected rock vapor expands and rapidly cools, condensing to droplets whose estimated radii are $r \sim 0.1$ to 1 cm for v_i = 20 to 30 km s^{-1} impacts [11]. Collisions between ejected particles occur on a timescale $\tau_{ej} \sim \rho r/(\Omega\sigma)$, where ρ is particle density, $\sigma = M_{ej}/(2\pi a\Delta a)$ is the ejecta surface density, M_{ej} is the total ejecta mass, a is the source moon's semi-major axis, Ω its orbital frequency, and $\Delta a \sim 2ae$. With $M_{ej} \sim 10^{20}$ g and $e \sim 0.3$ (e.g., Fig. 1), $\sigma \sim 0.03$ g cm^{-2} at Tethys's orbit, implying $\tau_{ej} \sim (r/1\text{-cm})(2\pi/\Omega) \sim 10$ orbits. The collision time with Tethys itself is $\tau_{sat} \sim 2\pi a\Delta a/\ (\Omega\pi R_T^2)$, which for $R_T \sim 500$ km and $e \sim 0.3$ is ~ 10^5 orbits. Because $\tau_{ej} << \tau_{sat}$ for a wide range of initial ejecta sizes, ejecta will self-collide into a disk and grow through mutual collisions until they eventually impact a satellite. Collisions rapidly damp eccentricities and inclinations, but exchange angular momentum much more slowly, so that an ejected particle initially on a highly eccentric orbit will collisionally damp to an approximately circular orbit with semi-major axis a_{eq} that has the same specific angular momentum normal to the planet's equatorial plane (l_z) as the particle's initial orbit, with $a_{eq} \equiv l_z^2/GM_P$, where M_P is Saturn's mass. An initial ejecta orbit with $e = 0.3$ and a periapse (apoapse) at Tethys's orbit ($a = a_T$) would then damp to $a_{eq} \sim 1.3a_T$ (~ $0.7a_T$), or to orbits that overlap those of Enceladus and Dione. At Mimas (with $a = a_M$) a comparable eccentricity leads to $a_{eq} \sim 1.3a_M$ (~ $0.7a_M$), and to orbits that cross that of Enceladus and pass just exterior to the B ring.

Where an impactor's rock ultimately accretes will thus be a function of its post-impact evolution. It seems likely that a given degree of impactor material mixing between neighboring satellites will tend to decrease the net rock accreted onto Tethys and increase the net rock accreted onto Enceladus and Dione compared to the $M_{r,LHB}$ estimates in Table 2. These estimates also assume the current satellite properties. The observed loss rate of H_2O from Enceladus [12]—if it were applicable to its entire history—would imply an initial object with ~10^{23} g more ice, whose larger radius would lead to impact rates and $M_{r,LHB}$ values about a factor of two larger than in Table 2.

OSS-LHB impactors small enough to be directly captured by passage through the rings would be expected to contribute little rock to the rings, due to the relatively small number of such objects in the shallow size distribution inferred for impactor radii < 1 km [13]. However ejecta from Mimas could deliver some rock to the rings.

Conclusions: An OSS-LHB delivers a mass in rock to Mimas, Enceladus and Tethys comparable to the total rock in these satellites. It thus would have substantially altered their primordial rock contents. Determining the rock mass accreted by each moon requires modeling the dynamical evolution of the impact ejecta.

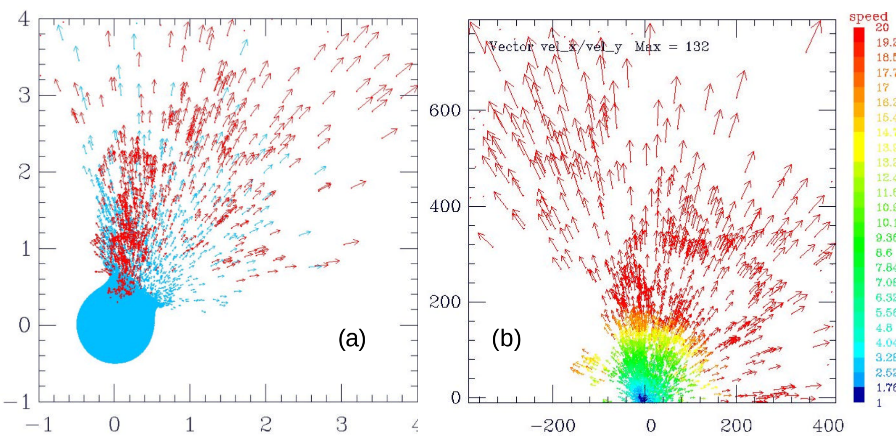

Figure 1. SPH simulation of a 30-km radius impactor hitting Tethys with v_i = 21 km s^{-1} at a 45° impact angle. Distances are shown in units of 10^3 km. (a) Target [blue] vs. impactor [red] particles at t = 0.1 hr. (b) t = 10.8 hr; color scales with speed in units of 0.26 km s^{-1}, with red particles having $|v| >$ 19. Tethys' escape velocity (0.4 km s^{-1}) is 1.5 in these units (darkest blue).

References: [1] Canup, R. M. (2010) *Nature* 468, 943-946; [2] Tsiganis, K. et al. (2005) *Nature* 435, 459-561; [3] Gomes, R. et al. (2005) *Nature* 435, 466-469; [4] Batygin, K. & M. E. Brown (2010) *Astrophys. J.* 716, 1323-1331; [5] Malhotra, R. (1995) *Astrophys. J.* 110, 420-429; [6] Fernandez, J. A. & W. –H Ip (1984) *Icarus* 58, 109-120; [7] Hahn, J. & R. Malhotra (1999) *Astron. J.* 117, 3041-3053; [8] Zahnle, K. et al. (2003) *Icarus* 163, 263-289; [9] Pierazzo, E. & H. J. Melosh (2000) *Meteor. Plan. Sci.* 35, 117-130; [10] Melosh, H. J. (1989) "Impact Cratering", Oxford Press; [11] Benz, W. et al. (2007) *Space Sci. Rev.* 132, 189-202; [12] Fleshman, B. L. et al. (2010) *AGU Fall Mtg*; [13] Dones, L. et al. (2009) *In Saturn from Cassini-Huygens*, Springer, 613-635.

Acknowledgements: This work is supported by NASA's Planetary Geology & Geophysics program.