The Role of Ejecta in Mid-Sized Saturnian Satellites' Crater Distributions. E.B. Bierhaus[1] , L. Dones[2] and K.J. Zahnle[3], [1]Lockheed Martin Space Systems Company (edward.b.bierhaus@lmco.com), [2]Southwest Research Institute, [3]NASA Ames Research Center.

Introduction: To derive accurate ages using impact craters, in either the relative or absolute sense, one must first determine the sources of impactors that make craters. Impact craters can be primary, secondary or sesquinary. *Primary* craters are made by direct impact of comets or asteroids. *Secondary* craters are the result of essentially ballistic trajectories of ejecta from the primary crater to some distance away. For typical heliocentric impact speeds of heliocentric comets onto Saturnian satellites of several to 30 km/s [1], ejecta can be launched at speeds from a few hundred m/s to several km/s. When an ejectum is launched at a speed faster than the escape velocity of a moon, it can go into orbit about the planet. Most escaped ejecta are eventually swept up by the source moon, but the orbits of some escaped ejecta can be sufficiently perturbed that the ejecta will impact another satellite [2]. In either case, craters formed by ejecta that initially escape their parent object are called *sesquinary* craters [3]. Because secondary and sesquinary craters are products of primary craters, and because the larger (and therefore generally older) primary craters create the most ejecta, older terrains will have both the greatest number of primary craters, and the greatest contamination from secondary and sesquinary craters.

Important Background: Voyager-based analysis crudely divided Saturnian craters into two populations, called Population I and Population II. Population II follows a steeper size-frequency distribution than Population I (i.e., in relative terms, Population II has a smaller number of large craters). One hypothesis proposed (e.g. [4]) that heliocentric comets are responsible for Pop. I, while planetocentric debris is responsible for Pop. II. A second hypothesis (e.g. [5]) proposed that planetocentric debris largely is responsible for both populations.

Since the Voyager flybys, a number of developments have taken place. First is the determination that heliocentric comets dominate the impactor population of the outer solar system [6-8]. Second is the resurrection of Shoemaker's [9] observation that secondary craters can be a major component of the small cratering record [10-12]. Third is the detailed modeling of the dynamical behavior of escaped ejecta in multi-body systems (such as the Saturnian system), leading to the first quantitative estimate of the effect of sesquinary ejecta on the cratering population [2]. Fourth is the ongoing laboratory and analytical work into the physics of crater ejecta [e.g. 13, 14]. Fifth is the possible origin of irregular satellites of the giant planets, and possible consequences of their collisional evolution for the cratering record on inner satellites [15]. The capstone, of course, is the presence of the Cassini mission at Saturn, and the imaging data that enables a significant improvement of the catalogue of craters [e.g. 16-17].

New Crater Measurements: We have made crater measurements on Enceladus, Hyperion, and Rhea. Enceladus's young terrains are sufficiently crater-free that they should provide a reasonably uncontaminated picture of the recent primary crater population (small primary craters accumulate the fastest, and contribute the least to secondary and sesquinary craters). Hyperion's escape velocity is sufficiently small (< 100 m/s) that any ejecta it retains move too slowly to form secondaries, so any craters seen must be primary or sesquinary craters. Rhea is a much older terrain with sufficient surface gravity to form secondaries, and therefore expresses an "integrated" exposure of primary, secondary, and sesquinary sources.

Enceladus. Our measurements of craters on young terrains on Enceladus produce a roughly -2 differential power-law slope for craters < 10 km diameter (vs. -3.5 for Dohnanyi's size-independent collisional cascade). Measurements on older terrains (our measurements and others, e.g. [16]) indicate a steeper slope, approaching or even exceeding a -3 differential slope.

Hyperion. Craters < 10 km diameter on Hyperion reveal a slope that is more shallow than a -2 differential power-law slope. However, there may be unusual or poorly understood degradation processes on Hyperion that could preferentially remove small craters, so we are not yet confident that these data are "clean" measurements of the crater population.

Rhea. Our data for Rhea show a roughly -3 differential power-law slope for craters between 2 and 20 km. Although our measurements cover a small portion of the Cassini images, the results are in general agreement with the more extensive measurements of [17].

Analytical Work: Using the most recent summary of laboratory measurements of cratering ejecta [14], and heliocentric impact velocities from [1], we estimated the relative fraction of ejecta masses for a hypothetical 1 km diameter cometary impactor on various Saturnian satellites. We calculated the fraction of ejecta mass available to make secondaries, f_{sec}, and the fraction of ejecta mass available to make sesquinaries, $f_{1.5}$. This requires estimating the minimum velocity required (v_{min}) to make secondary craters. Based on observations of secondaries around craters on Europa, this could be as low as 150 m/s, the value we use here. (Although the actual value could differ, general trends described here would not change).

Figure 1 plots f_{sec} vs. $(v_{esc} - v_{min})/v_{esc}$ for some Saturnian satellites (open circles), as well as for Europa, Ganymede, and Callisto for comparison. Here v_{esc} is the escape velocity of a satellite. This plot demonstrates that when v_{esc} is near v_{min} (e.g. Mimas or Enceladus), few of the ejecta are available to make secondaries. In contrast, when v_{esc} is much larger than v_{min}, more of the ejecta are available to make secondaries.

Of particular note is the contrast between the relatively low-mass Saturnian icy satellites and the big icy Galilean satellites. The higher escape speed of the Galilean satellites means far more ejecta are retained to make secondary craters. This explains why on Europa clusters of secondary craters are everywhere [11], despite a very low density of large primary craters, and yet clusters of secondary craters are rare to non-existent on Saturnian satellites. The low surface gravity of the Saturnian satellites means that even the low-speed ejecta can travel far from their parent primary, and the highest-speed spalled plates [13] (that form distant secondaries on the Galilean satellites or the Moon or Mars) simply go into orbit about Saturn.

Figure 2 plots $f_{1.5}$ vs. $(v_{esc} - v_{min})/v_{esc}$ for some Saturnian satellites (open circles), as well as for Europa, Ganymede, and Callisto (filled circles). As expected, the behavior is the inverse of Fig. 1. A greater fraction of the ejected mass is available for sesquinary craters from the low-mass objects than for the high-mass objects. Even if much of the escaped ejecta is eventually reaccumulated on its parent object, sesquinary craters lose the clustering behavior of secondary craters.

Preliminary Observations: We are still working on several aspects of the chronological evaluation of the Saturnian system, but based on our current work we offer the following prelimary observations:

1. Crater size-frequency distributions on the young terrains of Enceladus are similar to the primary crater populations seen on Europa, both of which have a differential slope of roughly -2. This suggests that small comets (less than a few hundred meters diameter) may have a roughly -2 differential slope as well.

2. The low-mass Saturnian satellites (e.g. Mimas, Enceladus) generally may lack signs of traditional secondary craters (e.g. clustering) seen on other cratered surfaces because their escape velocity is so low.

3. Ongoing accumulation of a -2 differential slope impacting population could lead to a steeper differential slope crater population by the accumulation of sesquinary craters. In general, sesquinary ejecta preserve [2] the inverse mass-velocity distribution of ejecta [e.g. 12], so should contribute a steeper than -2 component to the crater size-frequency distribution, while eliminating the clustered behavior of secondaries.

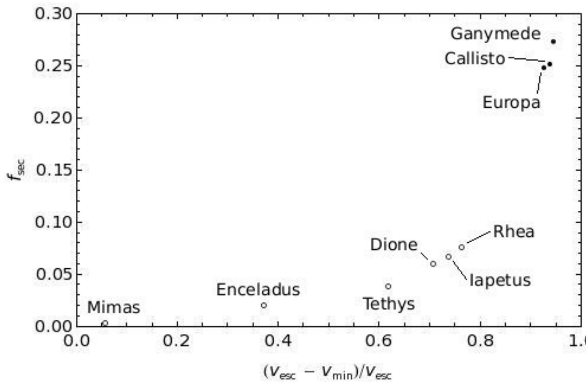

Figure 1: The fraction of ejected mass that is available to make secondary craters, f_{sec}, for select Saturnian satellites (open circles) and Galilean satellites (closed circles).

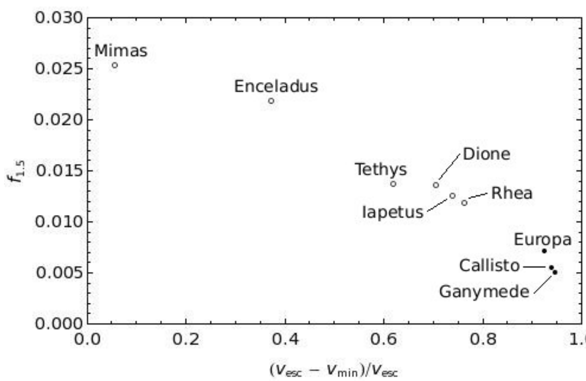

Figure 2: The fraction of ejected mass available to make sesquinary craters, $f_{1.5}$.

References: [1] Zahnle K.J. et al. (2003) *Icarus*, *163*, 263–289. [2] Alvarellos J.L. et al. (2005) *Icarus*, *178*, 104-123. [3] Zahnle K.J. et al. (2008) *Icarus*, *194*, 660–674. [4] Chapman C.R. & McKinnon W.B. (1986) in *Satellites*, 492-580. [5] Strom R.G. & Woronow A. (1982) *LPS 18*, 966-967. [6] Shoemaker E.M. & Wolfe R.F. (1982) in *Satellites of Jupiter*, 277-339. [7] Levison H.F. & Duncan M.J. (1997), *Icarus*, *127*, 13-32. [8] Zahnle K.J. et al. (1998), *Icarus*, *136*, 202-222. [9] Shoemaker E.M. (1965), in *The Nature of the Lunar Surface*, 23-77. [10] McEwen A.S. et al (2005), *Icarus*, *176*, 351-381. [11] Bierhaus E. B. et al. (2005), *Nature*, *437*, 1125-1127. [12] McEwen A.S. & Bierhaus E.B. (2006), *Ann. Rev. Earth Planet. Sci.*, *34*, 535-567. [13] Melosh H.J. (1984), *Icarus*, *59*, 234-260. [14] Housen K.R. & Holsapple K.A. (2011), *Icarus*, in press. [15] Bottke et al. (2010), *Astron. J.*, *139*, 994-1014. [16] Kirchoff R. K. & Schenk P. (2009), *Icarus*, *202*, 656-668. [17] Kirchoff R. K. & Schenk P. (2010), *Icarus*, *206*, 485-497.