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Black Rain: The Burial of Callisto and Ganymede in Irregular Satellite Debris

W. F. Bottke (1), D. Vokrouhlický (2), D. Nesvorný (1), and J. Moore (3)
(1) Southwest Research Institute and NASA Lunar Science Institute, 1050 Walnut St, Suite 400, Boulder, Colorado 80302, USA (bottke@boulder.swri.edu); (2) Institute of Astronomy, Charles University, V Holešovičkách 2, 18000 Prague 8, Czech Republic; (3) NASA Ames Research Center, Space Science Div., MS 245-3, Moffett Field, CA 94035

Abstract. The Nice model [1, 2] predicts the giant planets had numerous close encounters with one another ~ 4 Gy ago, and that these events led to the capture of ~ 0.001 lunar masses of comet-like objects on orbits consistent with the known irregular satellites [3]. From there, they experienced substantial collisional evolution, enough to grind themselves down to their current low-mass states [4]. Using numerical simulations, we show that in the Jupiter system, Poynting-Robertson (P-R) drag [5] drove most of the debris, in the form of small particles, onto Callisto and Ganymede. This likely explains why their most ancient terrains appear buried in a $\sim$ 50-200 m layer of dark carbonaceous chondrite-like material.

Motivating problem. Irregular satellites are dormant comet-like bodies that reside on distant prograde and retrograde orbits around the giant planets. They were likely captured during the violent reshuffling of the giant planets described by the Nice model [1, 2, 3]. As giant planet migration scattered > 20 Earth masses of comet-like bodies throughout the Solar System, a few found themselves near giant planets experiencing mutual encounters. In some cases, the perturbations were sufficient to capture the comets onto irregular satellite-like orbits via three-body reactions.

A problem with this scenario, however, concerns the observed size-frequency distributions (SFDs) of the irregulars, which have little mass and shallow power-law slopes for $D >$ 8-10 km (**Fig. 1**). In comparison, Jupiter's Trojans, which were probably captured at the same time from the same source population in the same abundance, are 100 times as massive (~ 0.001 lunar masses) and have steep SFDs, particularly between $100 < D < 200$ km. To explain this discrepancy, we invoke collisional evolution [4], where the irregulars self-destruct once caught (**Fig. 1**). With no place to go, the fragments should grind themselves down into small particles.

Nature of particles. The size range of these puta-

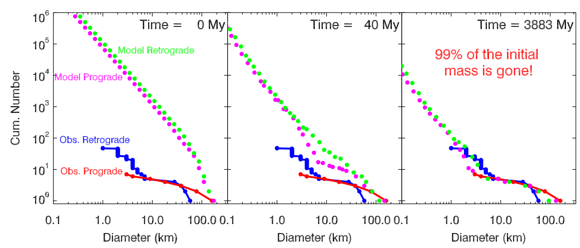

Figure 1: Snapshots of how Jupiter's initial irregular satellite populations undergo collisional evolution [4]. Most mass is eliminated in < 100 My.

tive particles is unknown, but insights can be gleaned from terrestrial micrometeorites, most which are primitive CM/CI-like bodies produced by the disruption of Jupiter-family comets (JFCs) [6]. Because JFCs come from the Kuiper belt/scattered disk, they represent members of the same source population that produced the irregular satellites. Measurements of micrometeorites from Antarctic water wells [7], as well as those inferred from impact craters on the LDEF and Genesis spacecrafts [8, 9], suggest their SFD peaks near $D \sim 200$ μm.

Irregular satellite particles with $D \sim$ 10-500 μm drifting inward by P-R drag [5] should eventually interact with or even hit the outermost Galilean satellites. We find this intriguing because the oldest terrains on Callisto and Ganymede are the darkest, and they spectrally look like water ice contaminated by a blanket of dark, non-icy material with spectral properties similar to CI/CM meteorites [10, 11].

Particle evolution. To test this, we computed the accretion efficiency of irregular satellite particles evolving down to the Jupiter's regular satellites. We tracked particles with $D =$ 10, 20, 50, 100, and 200 μm and bulk densities of 1 g cm^{-3}. Thousands of particles were assigned to each size and were given starting orbits with semimajor axis $a =$ 0.04-0.18 AU, eccentricity $e = 0$-0.7, and isotropic inclinations. The particles were removed if they hit a satellite, Jupiter, or they reached beyond 0.6 AU from the planet. **Fig. 2** shows the dynamical evolution of a representative $D = 50$ μm particle started on a retrograde orbit.

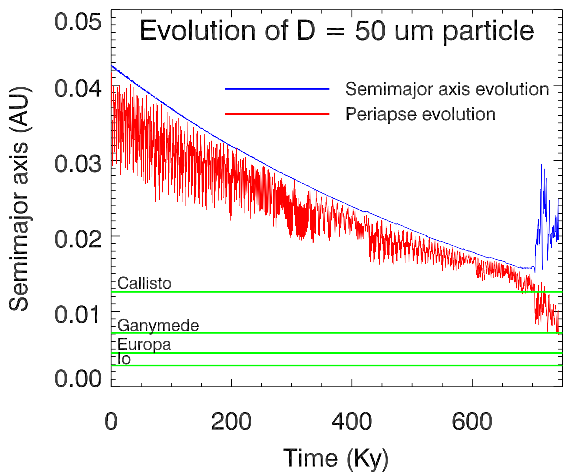

Figure 2: A $D = 50$ μm retrograde particle evolving quietly by P-R drag (i.e., no resonances encountered) until it scatters off Callisto and hits Ganymede.

Fig. 3 shows our net accretion statistics. Larger particles, with slower drift speeds than smaller ones, are more likely to be swept up by the outermost moons. This means that particles avoiding Callisto may reach Ganymede, and to a lesser extent, Europa (and Io). We find that $D > 50$ μm particles evolve slowly enough that 30-40% end up hitting Callisto. If we assume 0.001 lunar masses was in the form of such particles, it would produce a ~ 200 m layer on Callisto. This result is consistent with the quantity of dark lag material found there, with some material mixed into the upper few kilometers of Callisto's crust by impacts (**Fig. 4**) .

Our results are also consistent with the nature of Ganymede's dark, ancient terrains as well as the limited dark lag deposits found within Europa's young low-lying valleys [11, 12, 13].

Implications. Terrain brightness, when combined with our model results, may provide a alternative means for dating Galilean satellite surfaces (i.e., bright = young; dark = old). It would be interesting to compare such ages with those deduced from crater counts/impactor flux models.

The Saturnian and Uranian systems also had comparable irregular satellite systems in the LHB era [3, 4]. This may explain why many Uranian moons appear covered by a dark non-icy material similar to CI/CM

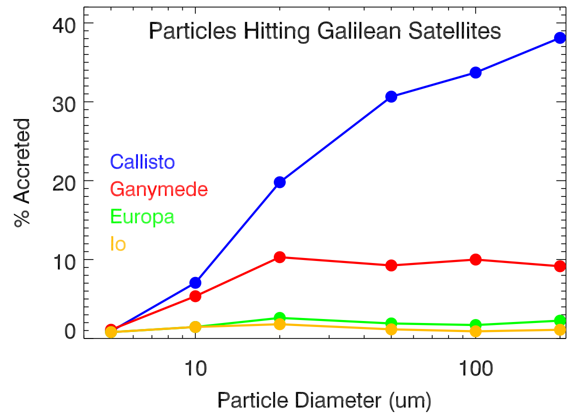

Figure 3: Net accretion of $D = 10$, 20, 50, 100, and 200 μm particles on the Galilean satellites.

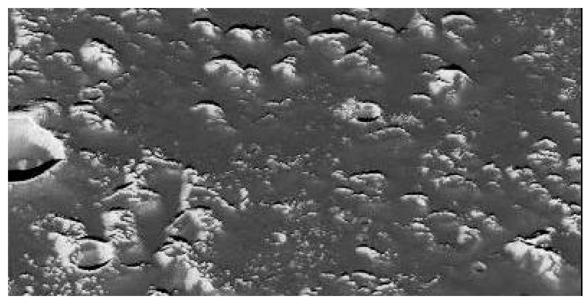

Figure 4: Close-up of Callisto's Valhalla crater.

meteorites. *Intriguingly, if Titan gets as much material as Callisto/Ganymede, it could provide alternative means for making its dark dunes*.

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