IMPACT-DRIVEN ICE LOSS IN OUTER SOLAR SYSTEM SATELLITES: CONSEQUENCES FOR THE LATE HEAVY BOMBARDMENT. F. Nimmo, D.G. Korycansky, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz CA 95064 (fnimmo@es.ucsc.edu, dkorycan@ucsc.edu).*

Summary We use the results of hydrocode simulations to determine how much ice is removed from outer solar system satellites during the putative Late Heavy Bombardment. Owing to gravitational focusing, the inner satellites Miranda, Mimas and Enceladus are predicted to have lost all their ice during the LHB, in contradiction to observations. Possible solutions to this paradox are either that the LHB delivered ~10 times less mass than the standard model, or that the inner satellites formed after the LHB.

Introduction Satellite impact velocities are a strong function of distance from the primary [1]. Thus, on the one hand inner satellites like Mimas may have experienced multiple disruptive impacts [2], while on the other outer satellites like Callisto and Titan can experience accretion and later bombardment without melting or fully differentiating [3].

The Late Heavy Bombardment (LHB) was originally proposed to explain clustering in the ages of lunar basins, but probably applied to at least all the terrestrial planets [4]. The Nice model [5] explains the LHB by a crossing of the 2:1 mean motion resonance between Jupiter and Saturn, in which case the outer solar system would have suffered an LHB [3,6]. According to the Nice model, the total impactor mass delivered to Callisto during the LHB was 3×10^{20} kg [3].

Model To calculate the effect of each impactor, we calculate the ratio of the vapor mass (M_{vap}) to impactor mass (M_i) using equation (13) of [7]. We assume ice-ice impacts with zero porosity and assume a temperature of 150 K to obtain conservative estimates of vapor production. We take the specific energy of melting to be 8.2×10^5 J kg^{-1}. We assume that any vapor produced is lost from the satellite. This is because the RMS thermal velocity of water vapor at 273 is about 0.6 km/s, which significantly exceeds the escape velocity of the small inner satellites. Thus, most vapor produced will escape the immediate vicinity of the satellite, after which it will condense and be removed (e.g. by sputtering or Poynting-Robertson drag). The ~ 100 yr lifetime of the E-ring round Enceladus [8] is an example of these effects.

To calculate the cumulative effect of all LHB impactors, we use a Monte Carlo approach similar to that used in [1]. Individual impactors are selected from a size distribution scaled to match the crater record on Iapetus [6], while the total mass of all impactors striking each satellite is scaled from the Callisto value (3×10^{20} kg) using the probabilities given in Table 1 of [1]. Individual impactor velocities are calculated using a procedure similar to [1]. We assume v_∞ =4.4 km/s, an inclination uniformly distributed between $+30^\circ$ and -30°, and collision impact angles uniformly distributed from 0 to 90°. We neglect the effects of satellite escape velocity on impact velocity. Fig 1a plots the total mass M_{imp} delivered to each satellite during the LHB, compared to the satellite mass M_{sat}. For some of the inner satellites (Umbriel, Ariel, Miranda, Enceladus, Mimas) this ratio exceeds ten percent, suggesting the importance of the LHB in these bodies' evolution.

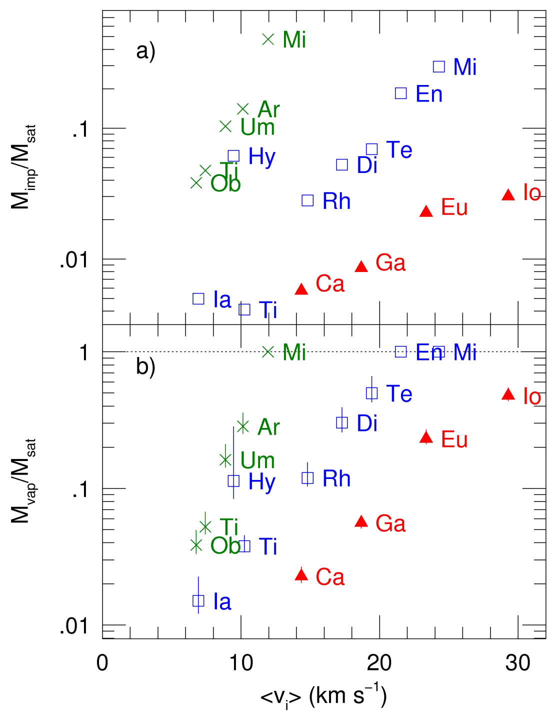

Figure 1: a) Total mass of impacting material as a fraction of satellite mass for satellites of Jupiter (filled triangles), Saturn (open squares) and Uranus (crosses), plotted versus median impact velocity. Individual satellites are indicated by the first two letters of their names. Total impacting mass for each satellite is derived from collision probabilities [1] scaled to 3×10^{20} kg at Callisto [3]. b) Mass of impact-produced vapor as fraction of satellite mass versus median impact velocity. The symbols are the median mass fractions from 1000 Monte Carlo trials. Error bars indicate the range from the 10th to 90th percentile results. Mimas, Enceladus and Miranda suffer complete vapor loss in every trial, so lack vertical error bars.

Because of the impactor size-frequency distribution adopted, most of the mass is contained in intermediate-size impactors (7.5-100 km). Roughly 10^2 bodies of radius 100 km would be required to provide the mass delivered to Callisto by the LHB. Thus, the stochastic nature of the impact process is likely to cause only small variations in the total impactor mass delivered (Fig 1a). This is important, because it is total impactor mass which mainly controls the total mass of vapor produced. Furthermore, because the impactors are generally small compared to the target, using the results of [7] is appropriate; it would not be for collisions between comparable-size objects.

Results Fig 1b shows the total mass of vapor produced relative to the satellite mass. The distributions of impact velocity and (especially) vapor production are highly non-Gaussian and asymmetric; to give an idea of the spread of these quantities, we draw “errors bars” on the plot that span the 10-90th percentile values. Since we assume that all vapor produced is removed, this figure demonstrates that Mimas, Enceladus and Miranda are expected to all have lost their entire volatile inventory. This conclusion is evidently in conflict with the ice-rich surfaces of these bodies.

Discussion The predicted volatile depletion of the innermost satellites is consistent with previous studies of their likely disruption [2,6]. However, both Miranda and Mimas contain more than 75% ice [9], in conflict with the predictions. Below we discuss four possible resolutions of this paradox.

1. Water could have been added after the LHB. However, integrating the total mass delivery over 4 Gyr based on impactor flux curve A of [1] does not result in enough material being added.

2. The stochastic nature of the impact process could have spared Mimas and Miranda a large collision. However, for this to have happened a very different size distribution from the one adopted by [6] and our study would be required.

3. The inner moons formed after the LHB. One possible mechanism for delayed satellite formation due to the expansion of a massive primordial Saturn ring has been proposed [10,11]. Other mechanisms, such as a giant impact on Uranus [12], might also have played a role. If the inner satellites are indeed younger than the LHB, then interpretations of their surface ages based on crater counts [1] will have to be significantly revised.

4. A perhaps more likely explanation is that the mass of the LHB we have invoked is too large. Reducing it by an order of magnitude would solve the problem. It would also reduce the likelihood of collisional disruption of the inner satellites [2,6] and make it easier to explain the apparent incomplete differentiation of Titan and Callisto [3]. A reduced LHB mass would also help to reconcile the observed abundance of noble gases in the terrestrial atmosphere with that predicted from delivery (via comets) during the LHB [13].

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References

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