# DESTRUCTION AND RE-ACCRETION OF OUTER SOLAR SYSTEM SATELLITES DURING THE LATE HEAVY BOMBARDMENT.

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**Introduction:** One explanation for the Lunar Late Heavy Bombardment (LHB) can be found in the Nice Model [1], [2]. In this model, an exterior disk of unaccreted planetesimals remains after the main stage of planet formation. Migration due to chance encounters with disk particles brings Jupiter and Saturn to a 1:2 mean motion resonance, causing a period of dynamical instability in the system. With the right choice of initial conditions, the timing of this period can be made to coincide with the timing of the suspected LHB [2].

The above scenario would also lead to a LHB period in the outer solar system and the possible ramifications for the small-to-middle sized satellites of the outer system have already been noted [3]. Here we present the latest results from an extensive Monte-Carlo study of collisional outcomes, focusing on the rate of *catastrophic* impacts. We find that, even with very conservative assumptions, Mimas, Enceladus, Tethys, and Miranda experience at least one catastrophic impact in every simulation. We consider the implications of this for present-day observed properties of these satellites.

**Method:** We simulate 200 randomized LHB events for many satellites of the outer solar system. We draw random impactor samples (sizes and orbits) from estimated probability distributions [4]–[6] until the total mass delivered to the target exceeds the relative fraction of impactor flux expected to be intercepted by that satellite [7]. We fix the absolute value of delivered mass, $M_{\mathrm{LHB}}^{\mathrm{sat}}$, by scaling to the value suggested in [8] for Callisto.

The result of an individual impact is determined by calculating $Q$, the effective specific energy of impact (in the target's rest frame), and comparing it with $Q_D^*$, the energy of an impact that is expected to disperse half the mass or a target of radius $R$, obtained with the scaling law

$$Q_D^* \approx 0.05\ \mathrm{J/kg} \times \left(\frac{R}{1\ \mathrm{m}}\right)^{1.188}.$$

This scaling law was derived from hydro-code simulations of gravity-regime collisions of ice bodies. In this study, we used the SPH code SPHERAL [9]–[11] to extend the results of [12] to targets in the 100-1000 km range [13].

If $Q > Q_D^*$ we increment a catastrophic impact counter. We also keep track of *super-catastrophic* ($Q > 2Q_D^*$) and *ultra-catastrophic* ($Q > 3Q_D^*$) impacts.

We make the conservative assumption that any ejected mass is quickly re-accreted onto the target. The target's mass and radius thus remain fixed throughout the simulation. This is a conservative approach since if a target were allowed to lose mass between impacts it would become progressively easier to disrupt.

We begin by setting $M_{\mathrm{LHB}}^{\mathrm{sat}}$ for each target to match $M_{\mathrm{LHB}}^{\mathrm{Callisto}}$ as suggested by [8]. We then scale down the delivered mass until all satellites survive 200 simulated LHBs without experiencing a catastrophic impact. The resulting statistics are described below.

**Results:** Figure 1 shows the fraction of Monte-Carlo runs that included at least one collision with energy greater than one, two, and three times $Q_D^*$, for 11 outer solar system satellites. Mimas, Enceladus, Tethys, and Miranda experienced a catastrophic impact in every simulation. In most runs, Mimas, Enceladus, and Tethys experienced *multiple* catastrophic impacts, including impacts with energy several times that required to completely disrupt them. These satellites would be heavily modified by a LHB no matter what assumptions we make about the impactor population or re-accretion efficiency. By contrast, the larger satellites (Europa, Ganymede, Callisto, and Titan) are not ex-

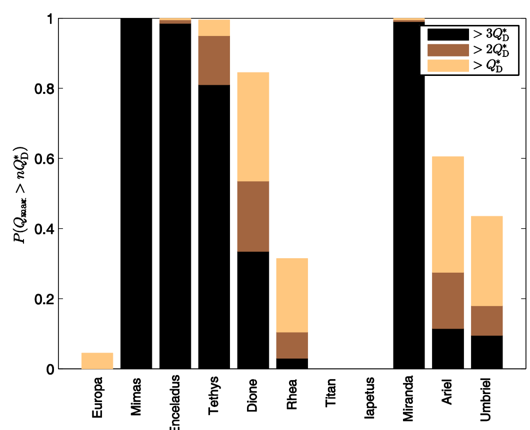


**Figure 1**. Fraction $P$ of Monte-Carlo runs that included at least one impact with effective specific energy greater than one, two, or three times the catastrophic disruption threshold, $Q_D^*$. In these runs the mass delivered to each satellite was scaled to deliver $\sim 3 \times 10^{20}$kg to Callisto.

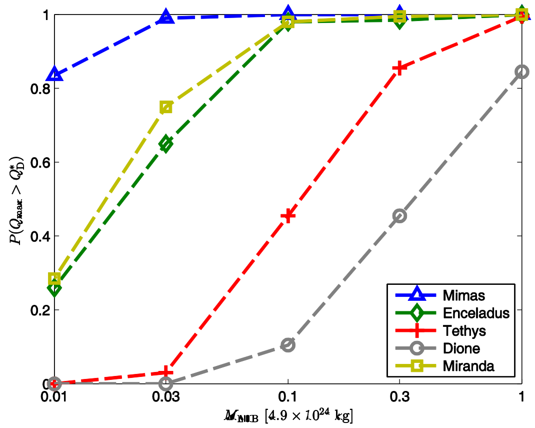


**Figure 2**. Fraction *P* of simulations that included at least one catastrophic impact, as a function of mass delivered. The upper limit value corresponds to $\mathbf{3 \times 10^{20}}$kg delivered to Callisto.

pected to undergo disruption; nor are very distant objects such as Iapetus.

It may be possible that different initial conditions in the Nice Model would result in less mass delivered to the outer solar system while still being able to explain the lunar LHB [14]. Figure 2 shows how the probability of catastrophic disruption drops when the total mass delivered in the simulation is reduced. A reduction by a factor of 3 is not enough to save Mimas or Enceladus, nor, probably, Tethys or Dione. The mass delivered by a hypothetical LHB must be at least 30 times less than the value predicted by the canonical Nice model to give Enceladus a decent chance of surviving the LHB unmodified, and 100 times less to give Mimas any chance at all.

**Implications:** The results described above suggest that the inner Saturnian and Uranian satellites were disrupted and re-accreted several times during the putative LHB. Possible implications of this scenario are:

(1) The impact history recorded on the surface of these satellites has been erased. This is consistent with current surface age estimates based on cratering rates [7]. Older surface ages are still conistent for larger satellites (Callisto, Umbriel, Oberon) or for the remotely orbiting Iapetus.

(2) The ice-rock ratio in differentiated bodies may have been affected. This is because, although we assumed perfect re-accretion in order to be conservative, in reality collisions are sure to lead to some mass loss. And probably preferentially that of lighter material. This mechanism can be invoked, for example, to explain the ice-rich nature of Tethys, arguing that Tethys is a byproduct of catastrophic disruption of a larger, differentiated body.

(3) The present day interior of Mimas is expected to be undifferentiated. This is because catastrophic disruption and prompt re-accretion is likely to “scramble” a pre-differentiated satellite. Conversely, if Mimas turns out to have a differentiated interior, then our results suggest either that Mimas is younger than 3.9 Ga, or that a heat source capable of melting Mimas must be invoked (accretional energy without radionuclides would not be sufficient), or that the canonical Nice Model – when applied to the outer solar system – requires significant modification. Interestingly, evidence for a complex interior of Mimas has indeed been suggested recently, based on anomalously large forced librations detected in Cassini Image Science Subsystem images [15].

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