OUTER-PLANET SATELLITE SURVIVAL DURING THE LATE HEAVY BOMBARDMENT (II).

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Introduction: To explain the abundance of large lunar basins with ages of ~3.9 Ga, the so called Late Heavy Bombardment (LHB), dynamical models have been suggested that invoke migration of the outer planets resulting in scattering inward of a planetesimal disk [1], [2]. These models predict a similar period of high impact fluxes in the outer Solar System. Combined with the higher collisional velocities possible due to gravitational focusing by the giant planets, an outer Solar System LHB may result not just in cratering, but in significant mass loss from some of the inner satellites of Jupiter, Saturn, and Uranus.

In a previous study, Nimmo and Korycansky [3] have shown, using estimates of impactor populations [4] and scaling laws for impact-induced vapor production [5], that many of the satellites of the outer Solar System would have lost significant fractions of their ice content during this period. Several satellites (Mimas, Enceladus, Miranda) could not have retained any ice at all, unless the total mass delivered to the outer Solar System by the LHB was a factor of ~10 lower than initially believed. (Recent re-evaluation [6] has, in fact, revised LHB planetesimal fluxes downward by ~3-5 times.)

In this work, we look again at the problem of satellite survival, this time from the point of view of disruption. That is, we calculate mass loss from the same collision statistics, but using scaling laws for the fraction of the target that would be shattered and dispersed, but not necessarily vaporized. We find that disruption is even more dangerous than vaporization, particularly for the inner satellites of Saturn and Uranus. But we also find that disruption is a highly variable process that depends strongly not only on the defined impactor population, but also on the particular sample from that population that happened to have impacted each target.

Method: We follow a similar approach to that used in [3], in turn based on procedures described in [7], [8]. Briefly, this is a Monte-Carlo approach. We simulate 100 randomized LHBs at each target (satellite), drawing impact samples (sizes and orbits) from estimated probability distributions [4], [7], [8], until the total mass delivered to the target exceeds the relative fraction of impactor flux expected to be intercepted by that satellite [9]. We fix the absolute delivered mass by scaling to the value suggested in [10] for Callisto. The result of individual impacts is determined by applying the scaling law of [11] (their eq. 6, with parameters recommended for the higher-velocity ice-on-ice impacts) for the largest remaining gravitationally bound fragment. When the scaling law implies that a fraction of the target mass was dispersed, we assume that this mass was preferentially ice, and reduce the target radius accordingly for future impacts.

Note that the threshold specific energy required for disruption, $\bar{Q}_D^*$, increases with increasing target size (in the gravity regime): $\bar{Q}_D^* \propto R^{1.26}$. As a result, targets become increasingly easier to disrupt as they lose mass. This means that simulated LHBs are different from each other not only by the coupling of different size impactors with different impact velocities, but also by the order the impacts occur. Our assumed size distribution of impactors is a segmented power law, dominated by the smallest impactors [4]. These small impacts usually result in no mass lost from the target at all, unless they come after a larger impact had already eroded the target.

The scaling law in [11] was originally shown to hold for targets of radius up to ~100 km. To extend it to ~1000 km targets, we have carried out a series of hydro-code simulations of impacts between ice bodies in the gravity regime, using the modern, parallel SPH code Spheral++ [12]. Fitting a line to the remaining mass fraction post-impact vs. the specific impact energy, we determine a threshold energy for disruption. Figure 1 shows our computed values of Q_D^* for three impact angles, next to the values obtained by [11] for smaller targets. The simple scaling law seems to hold quite well for these larger targets; we continue to validate it with more simulations. Other scaling laws and disruption criteria exist (see, e.g., [13]) and these can be substituted in our Monte-Carlo simulations. Our experiments so far suggest that, to first order, outcomes are insensitive to the choice of disruption criteria.

Results: Table 1 shows the fraction of mass lost to each of 17 major, present-day satellites of Jupiter, Saturn, and Uranus. The first column shown the median value over 100 Monte-Carlo runs, and the second and third columns show the minimum and maximum outcomes, respectively. Disruption seems to be mostly an all-or-nothing result. Mimas, Enceladus, Tethys, Dione, Hyperion, and Miranda, are destroyed in every run.

Io, Europa, Callisto, Iapetus, Titania, and Oberon, and of course Titan and Ganymede, are mostly unaffected. But note that extreme outliers do exist, in both directions! We attribute these to the small number of large, fast, impactors that are required for effective disruption.

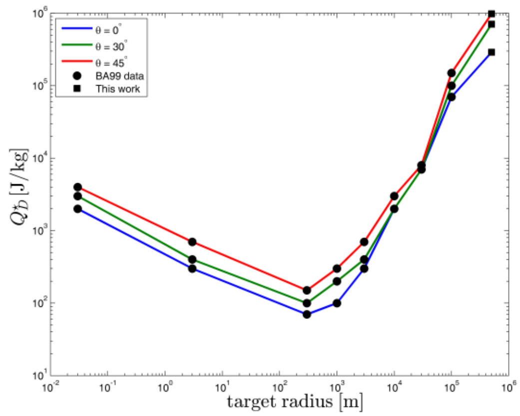

Figure 1. Threshold specific energy for disruption (in target's reference frame), as a function of target radius. Our latest simulations (square markers) extend the results of Benz and Asphau (circles) to the next order of magnitude target size.

Conclusion: On the face of it, these results suggest that disruption presents even more of a problem for the survival of the outer solar system satellites during the LHB than does vaporization [3]. There are several ways of potentially reconciling our results with the undoubted survival of these satellites.

1. The extent to which dispersed material is completely lost to the system needs to be investigated dynamically; rapid reaccumulation might significantly reduce the effectiveness of impact erosion (cf. [14]).

2. Our assumed size distribution of impactors is incorrect. Smaller, more numerous impactors would generate much less erosion than fewer, larger impactors.

3. The total mass delivered by the LHB to the outer solar system is smaller than originally envisaged by at least one order of magnitude [6]. This is another aspect of the problem that needs dynamical investigation.

4. The formation of the observed satellites post-dated the LHB [15].

Further investigation is clearly required. Nonetheless, currently it appears difficult to reconcile the relatively robust calculations presented here with a massive outer Solar System LHB.

Table 1. Mass fraction of satellites remaining after simulated LHB-like events.

Target	M_r/M_t[1]	M_r/M_t[2]	M_r/M_t[3]
Io	0.00	0.00	1.00
Europa	0.00	0.00	1.00
Ganymede	0.00	0.00	0.20
Callisto	0.00	0.00	0.42
Mimas	1.00	0.91	1.00
Enceladus	1.00	0.72	1.00
Tethys	1.00	1.00	1.00
Dione	1.00	0.72	1.00
Rhea	0.41	0.00	1.00
Titan	0.00	0.00	0.18
Hyperion	1.00	1.00	1.00
Iapetus	0.00	0.00	0.43
Miranda	1.00	0.94	1.00
Ariel	1.00	0.09	1.00
Umbriel	0.99	0.00	1.00
Titania	0.00	0.00	1.00
Oberon	0.00	0.00	1.00

[1] Remaining mass fraction, median over 100 runs.

[2] Remaining mass fraction, minimum over 100 runs.

[3] Remaining mass fraction, maximum over 100 runs.

References:

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