Outer-planet satellite survival during the Late Heavy Bombardment (II)

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1) The premise

To explain the abundance of large lunar basins with ages of ~3.9 Ga, the Nice Model [1,2] invokes a migration of the outer planets resulting in a Jupiter-Saturn resonance that destabilizes asteroid orbits in the Main Belt. The same model predicts also that excitation of Uranus and Neptune into eccentric orbits would lead to these planets penetrating, and destabilizing, an exterior planetesimal disk, resulting in an LHB-like period in the outer Solar System as well. With the high collision probabilities and impact energies caused by gravitational focusing of the giant planets, could an outer Solar System LHB cause significant, or even catastrophic, disruption to the inner satellites of Jupiter, Saturn, and Uranus?

2) Mass loss scales with impact energy

In the gravity regime, the fraction of target mass that remains bound after a head-on collision scales linearly with the specific kinetic energy of impact, Q [3,4]. Oblique impacts can be accounted for by considering only the fraction of impactor volume that intersects the target. The mass lost in a given impact can thus be predicted by comparing the effective impact energy Q, with Q^*_D, the energy required to disperse half the target mass.

We ran collision simulations with various impactor masses/radii into 500 km and 1000 km radius targets, using the SPH-based parallel hydrocode SPHERAL [5], and fit the remaining target mass fraction to

$$f = -0.5\left(\frac{Q}{Q^*_D} - 1\right) + 0.5, \qquad (1)$$

to derive Q^*_D for these targets.

Figure 1 shows our values for Q^*_D, next to values previously obtained [3] for smaller targets. It appears that, for ice targets in the gravity regime, Q^*_D follows the power law

$$Q^*_D(R) \approx 0.05\ \mathrm{J/kg} \times \left(\frac{R}{1\ \mathrm{m}}\right)^{1.188}. \qquad (2)$$

We can now estimate the mass lost in a typical outer Solar System collision.

Consider, for example, Mimas, the innermost satellite of Saturn. It has a radius of ~200 km, and a mass of ~3.8×10^{19} kg. By the power-law scaling, $Q^*_D \approx 10^5$ J/kg. A heliocentric planetesimal impacts at roughly the orbital velocity, $v_{orb} \approx 14$ km/s. A 10 km ice impactor, with a mass of ~4×10^{15} kg, delivers ~10^4 J/kg, enough to disperse 5% of the target's mass.

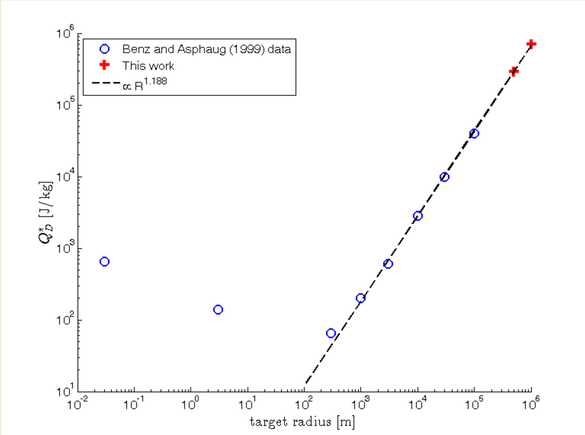

Figure 1. The threshold energy for disruption of ice targets as a function of target radius, obtained from SPH simulations.

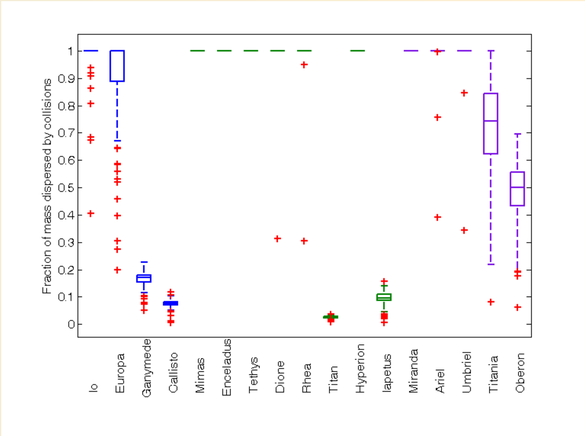

Figure 2. Fraction of satellite mass that was dispersed by collision. Boxes show the 25th to 75th percentiles of 200 Monte-Carlo runs, with the median denoted by a thick horizontal line. The whiskers extend to the minimum and maximum value not considered outliers, while the outliers are shown by red markers. Here, each Monte-Carlo run was stopped when the total mass delivered to the target exceeded its share of the total LHB delivered to the outer Solar System, fixed by assuming 3×10^{20} kg were delivered to Callisto [9].

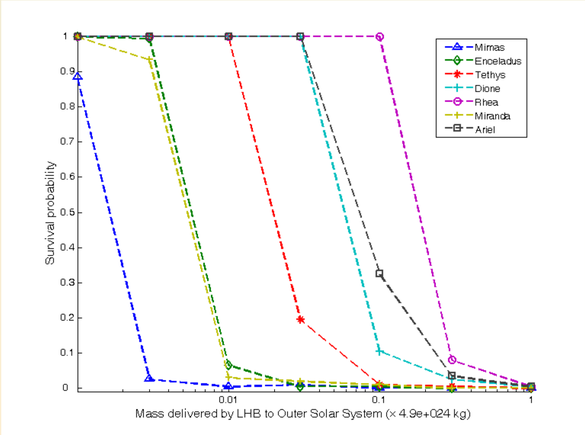

Figure 4. Probability of survival (fraction of runs resulting in less than half the target mass dispersed) as a function of total mass delivered by an outer Solar System LHB. The upper limit value corresponds to 3×10^{20} kg delivered to Callisto [9].

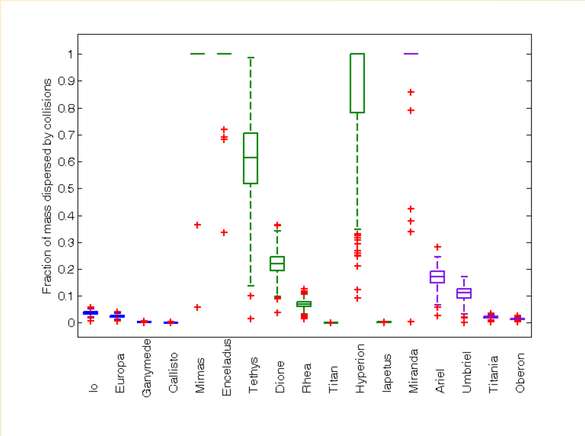

Figure 3. Same as fig. 2 but with the total delivered mass reduced by a factor of 30.

3) A Monte-Carlo LHB

The extent of destruction that a satellite may experience during an LHB-like period depends on the size and velocity of impacting material. To investigate possible outcomes of LHB events, we follow a procedure similar to that described in [6]. We simulate 200 randomized LHB events for each of 17 major, present-day satellites of Jupiter, Saturn, and Uranus, drawing impact velocities from probability distributions given in [6] and impactor sizes from a segmented power-law distribution scaled to match the cratering record on Iapetus [7]. The relative fractions of LHB-mass delivered to each target (Satellite) are calculated using the table given in [8], and the absolute delivered mass is a free parameter. For each impact, we calculate the dispersed mass using eqs. 1 and 2, and then reduce the target's radius accordingly.

Note that the threshold energy for disruption, Q^*_D, is a function of target size. Targets thus become increasingly easier to disrupt as they lose mass. This means that simulated LHBs differ not only by the coupling of different impactor sizes with velocities, but also in the order the impacts occur. Another strong stochastic variable is the number of large (>100 km) impactors drawn from the distribution.

Figure 2 shows the results of 200 Monte-Carlo runs, with the total delivered mass fixed by the value suggested by [9] for mass delivered to Callisto, and Figure 3 shows the same runs with that mass reduced by a factor of 30. The extent of destruction is severe, even for the lower value of delivered mass, and catastrophic for the canonical value. Figure 4 shows the probability of survival (defined as the fraction of Monte-Carlo runs that ended in less than half the target mass dispersed) as a function of the total mass delivered to the Jupiter system, for selected targets.

4) Conclusion

The scattering of a massive planetesimal disk onto the outer planets seems to be at odds with the abundance of ice-rich satellites with high orbital velocities. A possible solution to this problem would be to form these satellites after the LHB, or else to greatly reduced the predicted mass of the planetesimal disk. Alternatively, the impactor size distribution could be skewed towards smaller sizes. It is also possible that some of the mass dispersed by impacts could be re-accumulated. This idea requires further study.

References

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