CATASTROPHIC DISRUPTION OF ICY SATELLITES: PRELIMINARY RESULTS.

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According to current thinking, after the formation of the terrestrial planets giant impacts decreased on ~ 100 Ma timescales, as Moon- to Mars-sized bodies accreted onto the inner planets. The decline in impacts is widely thought to have been punctuated by the "Late Heavy Bombardment" (LHB), a hypothesized era of impact rates elevated about a thousandfold above the background in the inner Solar System some 3.8–4.1 billion years before the present. The notion of a Late Heavy Bombardment occurring a half billion years after planet formation originated with the dating of Apollo lunar samples thought to be from basins such as Mare Nectaris, Serenitatis, and Imbrium that are clustered in age around ~ 3.9 billion years.

One recently proposed theory for the cause of the LHB is the so-called "Nice Model", [1] in which the original architecture of the outer solar system post-formation was considerably different from that of the present day. In the model, the giant planets are pictured as orbiting in the region from ~ 5 to 14 AU, with a relatively massive ($\sim 35 M_\oplus$) planetesimal disk exterior to the planets extending to ~ 35 AU. Tidal scattering of the disk planetesimals induces gradual expansion of the outer planet orbits, and a crossing of the 1:2 mean motion resonance by Jupiter and Saturn excites destabilization of Uranus and Neptune into eccentric orbits that penetrate into the planetesimal disk. As noted by [2], large impactors in the outer solar system of trans-Neptunian would be expected to bombard any satellites that would have formed around the outer planets. Given the high orbital velocities of such satellites, disruptive and vapor-productive impacts would be expected to have occurred with significant frequency during this episode.

It has been suggested Saturn's satellites might not be primordial, due to massive disruptive impacts [6,7]. The location of satellites deep in the gravity well of a large planet poses a potential threat to their long-term survival [8]. It was recognized by [9] that the innermost Saturnian satellites likely suffered multiple disruptive collisions, owing to the large impact velocities caused by gravitational focusing.

We currently have only a very limited understanding of disruption in general, and satellite disruption in particular. One can imagine several disruption criteria, which we write here in terms of the radius of a disruptive impactor R_i with velocity v_i striking a target satellite of radius R_s. (Other relevant parameters include the densities ρ_i, ρ_s, and impact angle θ.) Some possibilities include equating the gravitational binding energy of the target to the kinetic energy of the impactor, yielding

$$R_i = (8\pi G/5)^{1/3}(\rho_s^{2/3}/\rho_i^{1/3})v_i^{-2/3}R_s^{5/3}, \qquad (1)$$

using crater scaling relations for impacts and equating the volume of the crater to that of the satellite [5]

$$R_i = [(13.5G\rho_s)^{\mu}/2.1]^{1/(3-\mu)}v_i^{-2\mu/(3-\mu)}R_s^{(3+\mu)/(3-\mu)} \qquad (2)$$

(with a typical value $\mu = 0.65$), or a catastrophic Q_D^* disruption criterion derived from numerical hydrodynamical impact simulations[3,4] of km-scale or planetary-scale objects

$$R_i = 5.8\times 10^{-2}(\rho_s^{0.466}/\rho_i^{1/3})v_i^{-0.4}R_s^{1.4} \qquad (3)$$

Monte Carlo simulations of outer-planet satellite survival during a bombardment episode have previously been carried out by us [8] using the Q_D^* criterion, which turns out to be the most conservative. We found that several mid-sized satellites of Saturn and Uranus had high probabilities of suffering catastrophically disruptive collisions, in particular, Mimas, Enceladus, Hyperion, and Miranda [cf.2,9].

Catastrophic Disruption Calculations using SPH

In this abstract we report preliminary results for catastrophic disruption calculations of icy target bodies in the range $50 < R_s < 1000$ km, using a Smooth Particle Hydrodynamics (SPH) code [10,11] that has been used in a number of impact studies, including km-scale objects [12,13,14], impacts onto Saturn's moons [15], the Moon-forming collision with the Earth [16], as well as large collisions modeling the formation of the Martian hemispherical dichotomy [17].

Table I

R_s	f	θ	$v_{1/2}$	notes
50	0.1	0	3.51	
50	0.2	45	1.81	
100	0.1	45	7.47	
100	0.2	45	1.97	
100	0.5	45	0.53	$t = 3.6\times 10^4$ s
250	0.2	0	3.15	
250	0.2	45	4.64	
250	0.2	60	6.00	
250	1.0	45	0.41	
500	0.5	45	1.97	
500	1.0	60	0.59	
1000	0.2	60	26.63	
1000	1.0	0	1.20	

Table 1: Cases for which (at present writing) we have found the critical velocity $v_{1/2}$ for which the mass of the largest fragment m_1 equals one half the initial target mass m_s. Columns give the initial target radius R_s in km, radius ratio $f = R_i/R_s$ of impactor to target radius, impact angle θ in degrees, and the critical velocity in km per second. One case has been measured at the indicated time.

Our targets were made of pure ice with radii $R_s = 50$, 100, 250, 500, and 1000 km; ratios of impactor to target $f = R_i/R_s$ were 0.1, 0.2, 0.5, and 1.0. Impact angles were $\theta = 0$, 45, and 60 degrees. While the we initially concentrated on impact velocities in the range expected for outer-planet system impacts ($7 < v_i < 37$ km s^{-1}), examination of our results led us to explore a lower-velocity range, down to $v < 0.5$ km s^{-1}. We used the Tillotson equation of state for the simulations. Simulations were done with $\sim 1.4 \times 10^5$ particles in the targets and matching resolutions (mass/particle) in the impactors.

Initial parameters for the calculations are the target radius R_s, impactor radius R_i, (or the ratio $f = R_i/R_s$), impact angle θ and impactor velocity v_i. Both targets and impactors are made of pure ice $\rho = 920$ kg m^{-3}, with the former objects having initial hydrostatically relaxed density profiles. We have been running the calculations for ≈ 10 gravitational times $(G\rho)^{1/2}$, or 4×10^4 sec.

We measured the degree of disruption in the calculation in terms of the mass m_1 of the largest fragment at the end of the calculation. We define m_1 as the largest unit centered at the potential minimum that is gravitationally bound (i.e. has kinetic + potential energy less than zero). The definition of “critical catastrophic disruption” for our runs is a largest fragment that is half the target mass, or $m_1 = 0.5 m_T$. For each combination of parameters R_s, f, θ, we ran cases with different velocities v_i to bracket the critical velocity $v_{1/2}$, yielding $m_1 = 0.5 m_T$., Have bracketed the value, we can interpolate to find the value $v_{1/2}$.

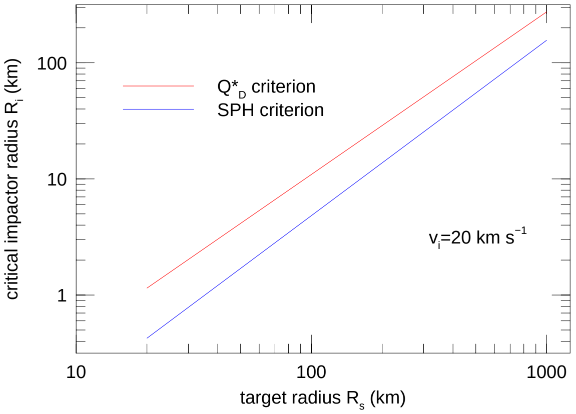

Figure 1: Radius R_i of disruption impactors vs. satellite radius R_s for impact velocities of $v_i = 20$ km s^{-1} for two criteria (disruption Q^*_D (Eqn. 3) and SPH (Eqn. 5)) discussed in the text.

Preliminary Results

We have run over 100 cases so far to explore the parameter space. At the time of writing, the calculations have yielded 13 sets of parameters that can be used to find the critical velocity $v_{1/2}$ as a function of R_s, f, and θ, as listed in table I. While we have not included density (of target or impactor) as a parameter in the simulations, we do have information on the dependence of critical impact velocity as a function of impact angle.

We have fit power-laws to the results listed in the table, yielding the velocity at which $m_1 = 0.5 m_s$. We find

$$v_{1/2} = 1.04 \times 10^{-2} R_s^{0.87} f^{-1.70} (\cos\theta)^{-0.55} \tag{4}$$

Re-arranging into the same formulation as Eqns. (1-3) gives

$$R_{1/2} = 6.78 \times 10^{-2} v_i^{-0.59} R_s^{1.51} (\cos\theta)^{-0.32} \tag{5}$$

where we write $R_{1/2} = R_i$ as the radius of the impactor with velocity v_i that yields $m_1 = 0.5 m_s$. Our result is qualitatively similar to that given by impact calculations done previously [3,4] and listed above as Eqn. 3, but as can be seen in Fig. 1, the critical value of R_i is somewhat smaller (and a steeper function of R_i) than found by the previous criterion. Our results give a critical radii $\sim 0.4 - 0.6$ times those found by previous studies [3,4]. Further simulations are required; however, if this result is borne out by continued work, we may expect that the conclusions of our previous work [8] regarding the survival of the outer-planet satellites will be confirmed.

Other issues needing investigation include the effects of the equation of state that is chosen for the simulations (Tillotson vs. other formulations such as ANEOS or SESAME) and the robustness of the results. We have found that the leading coefficient in Eqn. 5 is somewhat variable (to $\sim \pm 30\%$) as additional runs have been completed and added to the data set for fits to $v_{1/2}$. There is also the question of whether simulation run times of 4×10^4 s are sufficiently long to generate a robust result for m_1. Some simulations may require extended run times to produce definitive values. Another issue is that most of our results for catastrophic disruption are concentrated at relatively low velocities $v < 7$ km s^{-1}, whereas the bulk of satellite impacts will take place at $v \sim 20$ km s^{-1} due to the high orbital velocities around the outer planets; this implies that simulations with radius ratios $f < 0.1$ might also be required for maximal relevance to the question of small satellite survival.

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