CRATERING RATES IN THE OUTER SOLAR SYSTEM.

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Synopsis: We use several independent constraints on the number of ecliptic comets (aka JFCs) to determine impact cratering rates from Jupiter to Pluto. The impact rate on Jupiter by 1.5-km diameter ecliptic comets is currently $\dot{N}(d > 1.5\,\mathrm{km}) = 0.005^{+0.006}_{-0.003}$ per annum. Long period comets and asteroids are currently unimportant on most worlds at most sizes. The size-number distribution of comets smaller than 20 km is inferred from size-number distributions of impact craters on Europa, Ganymede, and Triton; while the size-number distribution of comets bigger than 50 km is equated to the size-number distribution of Kuiper Belt Objects. The gap is bridged by interpolation. It is notable that small craters on Jupiter's moons indicate a pronounced paucity of small impactors, while small craters on Triton imply a collisional population rich in small bodies. However it is unclear whether the craters on Triton are of heliocentric or planetocentric origin. We therefore consider two cases for Saturn and beyond: a Case A in which the size-number distribution is like that inferred at Jupiter, and a Case B in which small objects obey a more nearly collisional distribution. Known craters on Saturnian and Uranian satellites are consistent with either Case, although surface ages are much younger in Case B, especially at Saturn and Uranus. At Neptune and especially at Saturn our cratering rates are much higher than rates estimated by Shoemaker and colleagues [1], presumably because Shoemaker's estimates mostly predate discovery of the Kuiper Belt. We also estimate collisional disruption rates of moons and compare these to estimates in the literature [1,2].

Discussion: By placing a heavy weight on the historical record of close encounters with Jupiter we favor generally high impact rates, especially for comets larger than a few km diameter. In particular we conclude that the satellite systems of Saturn, Uranus, and Neptune are unstable against collisionally-induced evolution over the age of the solar system. At the smaller scale we reach the opposite conclusion: comets smaller than km-size are relatively rare and small primary craters are produced less frequently than one might expect. This latter conclusion is based on data at Jupiter, where the result is not really in doubt, but we have attempted to show that the same paucity of small comets is allowed by crater counts on the moons of the more distant planets (yet neither is it proved).

Among the questions directly addressed by our study, it is the collisionally-induced evolution of the satellite systems and the disappearance of small comets that seem most worth additional discussion. These questions may be related.

It is possible that comets smaller than km-size are rare among the current Kuiper Belt source of ecliptic comets. Crater counts in the outer solar system do not prove that small comets are abundant at Neptune or Saturn, although (unlike at Jupiter) small comets are permitted. Collisional lifetimes of the Uranian space-age moons are more consistent with an impacting population that lacks abundant small comets. Indeed the comet-size distribution we deduce at Jupiter gives lifetimes for the Uranian satellites that are all ~2 Gyr. The specific 2 Gyr time scale should not be taken too seriously, but that the disruption time scales for the different satellites are all about equal is an outcome specific to the Jovian (Case A) comet-size distribution. On the other hand more nearly collisional comet-size distributions (Case B) imply that the smaller moons have much shorter collisional lifetimes than do the larger moons. Moreover these lifetimes are quite short, typically <<1 Gyr. The implication is that the smaller moons are vanishing to the benefit of their larger neighbors; it becomes a puzzle that so many should exist now.

On the other hand there is a view that the Kuiper Belt needs to have been collisional at its current location. The argument is that densities two or three orders of magnitude higher than they are now are needed in order to spawn worlds like Pluto and QB1 *in situ* [3]. Such a thick swarm of bodies inevitably generates a lot of debris. If thereafter the Kuiper Belt evolved in a way that preserved the size-number distribution, small KBOs would now be abundant. It would therefore be required that most of the small comets vanish before they reach Jupiter, and perhaps before they reach Neptune. Near Jupiter one might ask whether CO2 or NH3 vaporization could be disruptive; at greater distances one might ask the same of CO, N2, or CH4. Comets are known to contain volatiles that can erupt beyond Saturn. Chiron is known to have been active at 13 AU and P/Halley had an outburst at 14 AU.

A second possibility is that in the course of losing the greater part of its primordial mass the Kuiper Belt shed its smaller comets preferentially. How this might have happened is open to speculation. Perhaps the smaller fragments were carried off with the gas, leaving only the larger bodies in place.

A third choice is to suggest that the larger bodies in the Kuiper Belt formed nearer the Sun, in rough analogy to how Neptune and Uranus may have formed in the vicinity of Jupiter and Saturn, only later to be scattered to greater distances [4]. Migration would obviate the need for *in situ* collisional evolution, and so no large population of small comets need form at the Kuiper Belt's distance in the first place. Such a model might introduce its own suite of difficulties, but it has the advantage of directly confronting the well-founded theoretical expectation that the solar nebula did not go on forever: that it had an outer limit.

[1] Smith B. et al. (1981) *Science 215,* 163; Smith B. et al. (1982) *Science 215,* 504; Smith B. et al. (1986) *Science 233;* 43; Smith B. et al. (1989) *Science 246,* 1422, 1986, 1989) *JGR, 90,* 1151–1154. [2] Lissauer J.(1988) *J.G.R. 93,* 13776; Colwell J. (2000) *J.G.R. 105,* 17589. [3] Stern S.A. (1995) *A.J. 110,* 856; Kenyon S. (2002) *P.A.S.P. 114,* 265. [4] Thommes, E. et al. (2002) *A.J. 123,* 2862.

Figure caption. Data points refer to various estimates of the impact rate at Jupiter, with the exception of the Centaurs, which refers to the impact rate at Saturn. The lines give the slopes of the size-frequency distributions as obtained from craters on Europa, Ganymede, and Triton, and from the observed populations of Kuiper Belt objects (plotted through the Centaurs). Generous error bars are to remind the authors that uncertainties are large. Case A refers to the relative abundance of small comets at Jupiter. Case B refers to the relative abundance of small comets at Triton; this latter assumes that the craters on Triton are made by comets. Case C is representative of the expected mass distribution of small comets from a collisional Kuiper Belt. Also shown for comparison are impact rates on Jupiter by Trojan asteroids and nearly isotropic comets (NICs). The former is a lower limit because it considers only dynamical loss from the L4 and L5 swarms; if collisional losses are important the impact rate at Jupiter is increased proportionately.