COLLISIONAL EVOLUTION OF THE PRIMORDIAL KUIPER BELT, SCATTERED DISK, AND TROJAN POPULATIONS.

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Introduction. The Kuiper belt, scattered disk, Oort cloud, and Jupiter/Neptune Trojans were derived from a primordial Kuiper belt (PKB) that likely once existed beyond 20 au. The end of the PKB was brought about by Neptune migrating through it at some early time, triggering a giant planet instability that led to our system of planets and small bodies [e.g., 1].

Up to now, this scenario has mainly been tested using dynamical models, but enough progress has been made to now consider collisional processes and their constraints. For example, a major challenge for any model is to explain the paucity of primary $D < 10$-20 km diameter craters found on Charon, Arrokoth, Europa, and Ganymede [2-3]. Collectively, these crater data indicate the KBO size frequency distribution (SFD) between $d \sim 30$ m and ~1 km is remarkably shallow (i.e., cumulative power law slope of $q \sim -1$) [4].

Here we use *Boulder* [5] to model collisional evolution of the PKB/daughter populations. For constraints, we employed (i) crater SFDs on icy satellites and KBOs [e.g., 2-3; 6-7], and (ii) observed SFDs of populations derived from the PKB (e.g., Jupiter's Trojans) [8-9]. Note that craters on icy satellites allow us to infer the SFD of the PKB population scattered onto planet-crossing orbits as well as the portion that went to the scattered disk (i.e., source of Centaurs/JFCs).

Model Setup. *Boulder* requires several input parameters that we get from other models.

First, for the initial SFD of the PKB, we gave it a shape taken from hydrodynamical simulations of the streaming instability (**Fig. 1**) [10]. The initial mass was set to ~30 Earth masses; most in $d \sim 100$ km objects and relatively few in $d < 100$ km objects. Note that the shape of this SFD is similar to the one predicted for the primordial asteroid belt [11].

Second, we delayed Neptune's entry into the PKB after the gas disk was eliminated by $t_{delay} = 0$ to 50 Myr [1]. Longer values of t_{delay} mean more collisional evolution takes place within a massive PKB excited by gravitational perturbations from a distant Neptune and embedded Pluto-sized bodies [4, 10].

Third, dynamical simulations [10] were used to calculate the intrinsic collision probability P_i, mean impact speed $V,$ and dynamical depletion values of objects residing within the PKB and those scattered into different daughter populations, such as those reaching giant planet-crossing orbits and those captured as Trojans.

Fourth, for each t_{delay}, we tested ~10^4 disruption law functions (i.e., Q_D* functions). They define the kinetic energy needed for a projectile to break up a target and > 50% of the ejecta away at escape velocity.

Model Results. To reproduce the shallow slope between 30 m and 1 km (and other constraints), we adopted Q_D* functions where the easiest body to disrupt from an energy/mass perspective was $d_{min} \sim 20$ m. A model SFD that matches data is shown in **Fig. 1**.
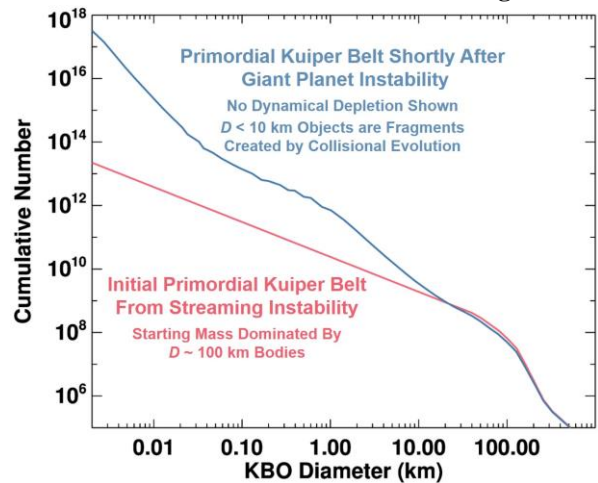
Fig. 1. *Collisional evolution of primordial Kuiper belt.*

The wavy SFD comes from a collisional cascade. Large objects disrupt and create fragments. Those with $d < 20$ m grind into a Dohnanyi SFD with $q \sim -3$, a slope that also explains dust observed by New Horizons [4]. This steep SFD decimates $d > 20$ m objects, leading to $q \sim -1$ for 30 m $< d < 1$ km. This shallow branch means fewer projectiles exist to disrupt $d > 1$ km bodies, with a "bump" constructed near $d \sim 1$ km.

Similar grinding occurs in the main belt, but there d_{min} is ~200 m [11]. This leads to a similarly-shaped SFD, except $q \sim -1$ is between 200 m $< d < 2$ km and the steeper slope starts at $d > 2$ km [11]. ***This may explain why crater SFDs on icy satellites look like they were made by asteroids; the shape of our model SFD in Fig. 1 is not that different from the main belt SFD.***

Our model also suggests that most $d < 10$ km bodies are fragments of larger bodies. ***This may explain why observed comets often have shapes comparable to similar-sized asteroids***.

Our best-fit model SFDs depends on two coupled parameters: t_{delay} and the disruption law of large KBOs. If t_{delay} is a few Myr, KBOs act like weak ice from [12].

If t_{delay} is tens of Myr or more, KBOs act like strong ice and are harder to disrupt [e.g., 13].

Crater/Impactor Results. Our model SFD from **Fig. 1** can be compared to crater SFDs on different icy worlds. For example, primary craters from the Galilean satellites [6] are shown in **Fig. 2.** Using scaling laws discussed in [2], we find a match between model/crater SFDs. Comparable model/crater SFD plots can be made for most icy satellites and KBOs, provided we stick to craters made by $d > 1$ km projectiles [2, 7].
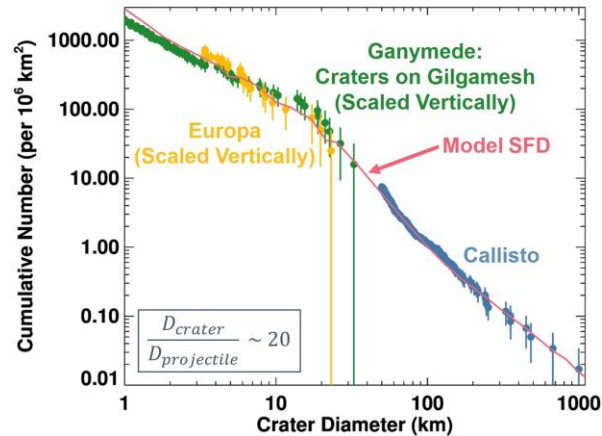
Fig. 2. *Primary craters on the Galilean satellites [6].*

It is more difficult to match crater SFDs made by $d < 1$ km projectiles because secondaries/sesquinaries often dominate primary crater populations [3]. Hyperion, however, avoids these issues, with the model SFD reproducing observed craters even at sub-km sizes [7].
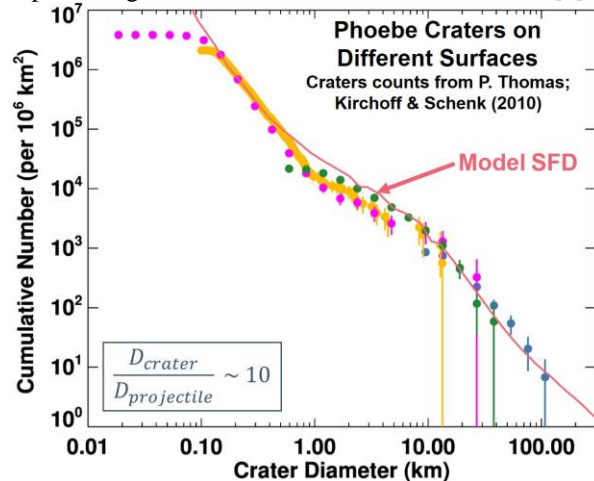
Fig. 3. *Phoebe craters counted by different authors.*

The steep SFD for $d < 20$ m also means ~20 $d > 10$ m projectiles hit Jupiter per year, a match to ground-based observations of Jupiter superbolide impacts [14].

Jupiter Trojans. A potential problem comes from the Jupiter Trojan SFD. Giant planet instability models show Trojans come from the PKB [1], yet the Trojan SFD, with $q \sim -2$ for $d < 100$ km bodies, does not match our model SFD (blue curve vs. black dots in **Fig. 4**) [8-9]. Collisional evolution among the Trojans over the last ~4 Gyr is also too limited to fix this [8].

The missing component may be collisional evolution taking place just prior to Trojan capture. Consider that enormous numbers of KBOs scattered out of the PKB readily move to ~5 au for a short time, where:

- Collision probabilities scale with heliocentric distance r as $P_i \sim r^{-3.5}$ [8] so P_i increases (25 au/5 au)$^{3.5}$ ~ 280 times near 5 au.
- Impact velocities go up (~5 km/s vs. ~2-3 km/s).
- To-be-captured Trojans move within a population equivalent of ~1% of the PKB for a few Myr.

Our model runs show this short yet substantial burst in collisional evolution can modify the SFD of the captured bodies, giving them a Trojan-like SFD (**Fig. 4**).
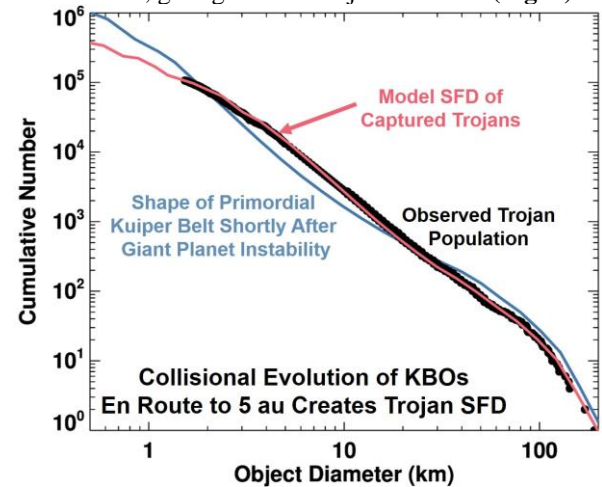
Fig. 4. *Collisions create Trojan SFD prior to capture.*

Implications. The spatial densities of $D > 10$ km craters on most Saturnian satellites are near saturation [7] (e.g., **Fig. 3**). By combining dynamical simulations from [8] with our impacting SFDs, we find the most ancient surfaces on these satellites are > 4 Ga. This challenges the idea many moons formed < 0.1 Ga [15].

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