COLLISIONAL EVOLUTION OF THE PRIMORDIAL KUIPER BELT, SCATTERED DISK, AND TROJAN POPULATIONS. W. F. Bottke[1], R. Marschall[2], D. Vokrouhlický[3], D. Nesvorný[1], A. Morbidelli[2], R. Deienno[1], M. Kirchoff[1], S. Marchi[1], H. Levison[1]. [1]Southwest Research Institute, Boulder, CO, USA (bottke@boulder.swri.edu), [2]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France. [3]Institute of Astronomy, Charles University, Prague, Czech Republic.

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 ~ 30 m and ~1 km is remarkably shallow (i.e., cumulative power law slope of q ~ -1) [4].

Here we use *Boulder* [5] to model collisional evolution of 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 those that went to the scattered disk (i.e., source of Centaurs/JFCs).

Model Setup. *Boulder* requires several input parameters derived 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 ~ 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 get a shallow slope between 30 m and 1 km (and other constraints), we had to adopt Q_D* functions where the easiest body to disrupt from an energy/mass perspective was d_{min} ~ 20 m. A model SFD that matches constraints is given in **Fig. 1**.

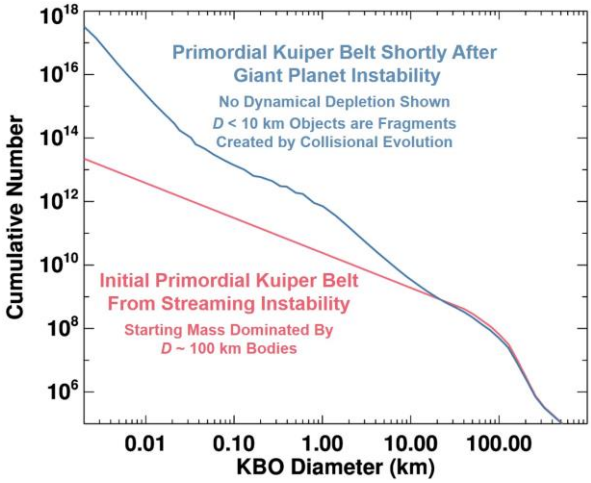

Fig. 1. *Collisional evolution of primordial Kuiper belt.*

The wavy SFD comes from a collisional cascade. Large objects disrupt and create fragments. KBOs with d < 20 m grind into a Dohnanyi SFD with q ~ -3 (a slope that also explains dust observed by New Horizons [4]). This steep SFD decimates d > 20 m objects, leading to q ~ -1 for 30 m < d < 1 km. In turn, this shallow branch means fewer projectiles exist to disrupt d > 1 km bodies, making a "bump" near d ~ 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 ~ -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 disrupt like weak ice from

[12]. If t_{delay} is tens of Myr or more, KBOs need to be harder to disrupt and act more like strong ice [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].

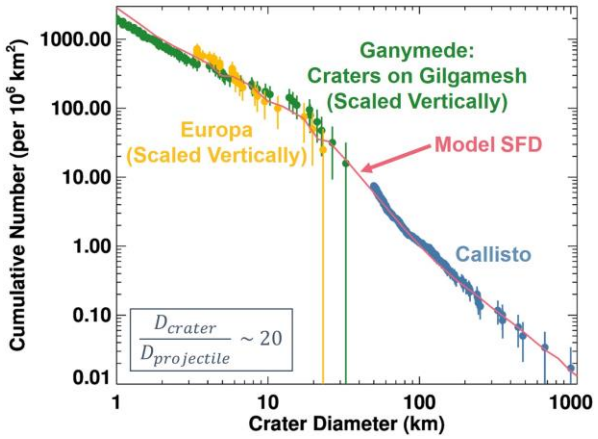

Fig. 2. *Primary craters on the Galilean satellites [6].*

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

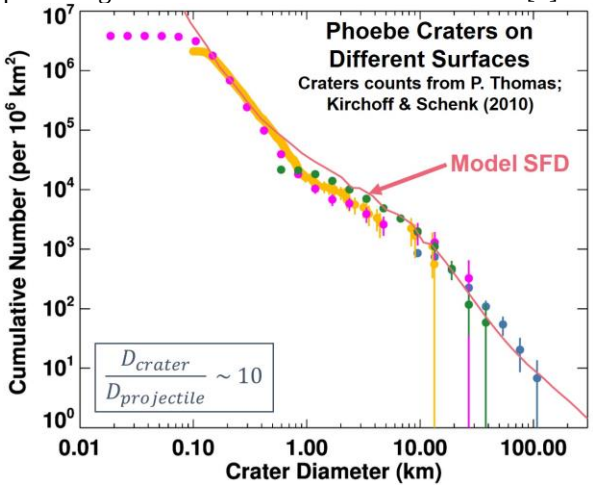

Fig. 3. *Phoebe craters counted by different authors.*

Our steep SFD at small sizes yields ~20 d > 10 m impacts on Jupiter per year. This matches the observed rate of superbolide impacts on Jupiter [14].

Jupiter Trojans. A potential issue comes from the Jupiter Trojan SFD. Giant planet instability models show Trojans come from the PKB [1], yet the Trojan SFD, with q ~ -2 for d < 100 km bodies, does not match our model SFD (blue curve vs. black dots in **Fig. 4**) [8-9]. Trojan collisional evolution over the last ~4-4.5 Gyr is also too limited to fix this problem [8].

The missing component may be collisional evolution taking place prior to Trojan capture. Consider that Neptune's migration sends an enormous number of KBOs from the PKB to ~5 au over 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 speeds go up (~5 km/s vs. ~2-3 km/s).
- Prior to capture, proto-Trojans evolve for a few Myr within a population that is ~1% of the PKB.

Our model runs show this burst of collisional evolution can modify the SFD of the proto-Trojans prior to capture, giving them a Trojan-like SFD **(Fig. 4)**.

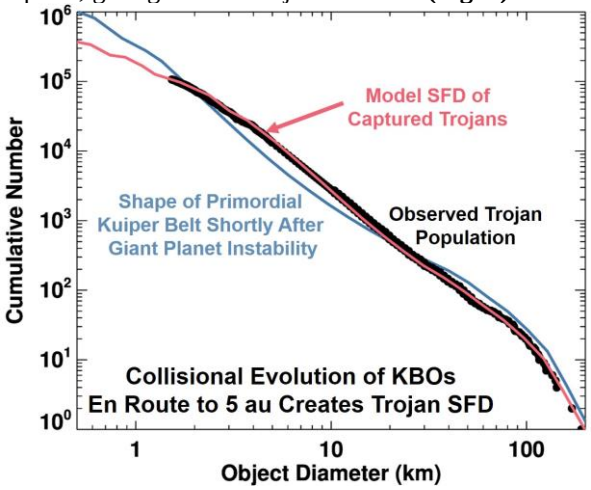

Fig. 4. *Collisions create Trojan SFD prior to capture.*

Implications. In preliminary work, we have combined our model SFDs with dynamical simulations from [8], satellite impact probabilities from [3], and crater scaling laws (e.g., [2]). Our results suggest most ancient surfaces on Saturn's satellites are > 4 Ga. This challenges the idea many moons formed < 0.1 Ga [15].

References. [1] Nesvorný, D. 2018. *Annu. Rev. Astro. Astrophys*. **56**, 137. [2] Singer, K., *et al*. 2019. *Science* **363**, 955. [3] Zahnle, K. *et al.* 2003. *Icarus* **163**, 263. [4] Morbidelli, A., *et al.* 2021. *Icarus* **356**, 114256. [5] Morbidelli, A. *et al.* 2009. *Icarus* **204**, 558. [6] Schenk, P. *et al.* 2004. In *Jupiter*, 427. [7] Kirchoff, M. & P. Schenk. 2010. *Icarus* 206, 485. [8] Wong, I. & M. Brown. 2015. *Astron. J.* 150, 174 [9] Yoshida, F. & T. Terai. 2017. *Astron. J* **154**, 71. [10] Nesvorný, D., 2018. *Nature Astro*. **2**, 878. [11] Bottke, W. F. et al. 2020. *Astron. J.* **160,** 14. [12] Leinhardt, Z., & Stewart, S. 2009. *Icarus* **675**, 542 [13] Benz, W. and E. Asphaug 1999. *Icarus* **142**, 5. [14] Hueso, R., *et al*. 2018. *Astron. Astrophys*. **617**, A68. [15] Ćuk, M. et al. 2016. *Astrophys. J*. **820**. 97.