EXPLORING THE MISSING EARLY HISTORY OF THE GIANT PLANET SATELLITES.

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

Motivation. There are many suggestive origin scenarios for the giant planet satellites. For example, some argue Saturn's satellites experienced a recent instability, with collisions creating a new set of satellites within the last 100 Myr [1]. Others postulate that the satellites of Saturn (and Uranus) formed in succession from a massive ring over many hundreds of Myr or more after the solar nebula dispersed [2]. It has also been hypothesized that the Saturn system recently lost a Rhea-sized satellite, which may have created its rings [3]. None of these scenarios, however, have been tested against the cratering records of the giant planet satellites. What do their craters tell us about the existing and missing history of the giant planet satellites?

Model. Here we use a new model of outer solar system bombardment to calculate the oldest surface ages for giant planet satellites. This involves tracking the collisional and dynamical evolution of the primordial Kuiper belt (PKB) that once existed beyond the initial starting location of Neptune (i.e., > 20 au).

Initial PKB. We assumed the PKB started with ~30 Earth masses, with most of the mass in the form of $D \sim 100$ km diameter bodies. Its initial size frequency distribution (SFD) (**Fig. 1; red curve**) was given a "bump" near 100 km, like the observed Kuiper belt, and a shallow SFD for smaller sizes (i.e., cumulative power law slope $q = -1$). The latter shape is consistent with Dark Energy Camera observations of the cold classical Kuiper belt [4], which is minimally evolved.

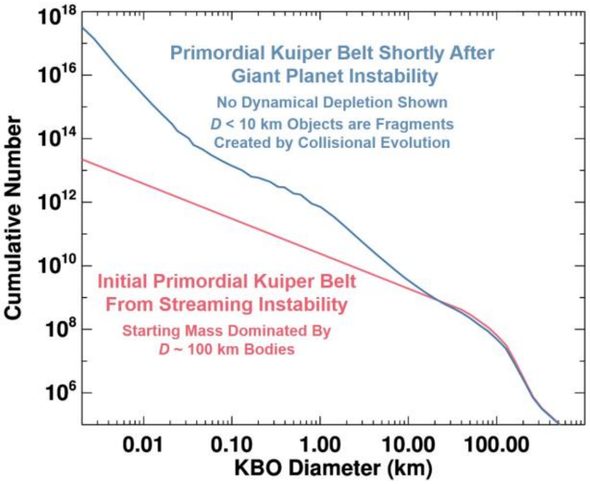

Fig. 1. *Collisional evolution of primordial Kuiper belt.*

Dynamical model. Our model results suggest the PKB lasted ~20 Myr after the dissipation of the solar nebula. At that time, Neptune entered the PKB and migrated across it, pushing the vast majority of the PKB's population onto giant planet-crossing orbits. This triggered a giant planet instability that led to our system of planets and small bodies [e.g., 5].

Using a dynamical model of PKB evolution [6], which can reproduce numerous solar system constraints (e.g., giant planet orbits, Kuiper belt, Oort cloud, Trojans, captured KBOs in main belt, etc.), we calculated the intrinsic collision probabilities P_i, impact speeds V, and dynamical depletion values of both PKB objects and those of the "*destabilized population*" that reached giant planet-crossing orbits (and the scattered disk). These bodies are the primary source of bombardment for the giant planet satellites over time.

Collisional Model. These parameters were input into the collisional evolution code *Boulder* [7]. Our goal was to find a solution that could reproduce (i) crater SFDs on icy satellites [e.g., 8] and (ii) the observed SFD of Jupiter's Trojans [9] for a solved-for disruption law. **Fig. 1 (blue curve)** shows a snapshot of our best fit results. The wavy SFD comes from a collisional cascade, with larger objects disrupting/creating fragments. We find $D < 20$ m objects grind themselves into a Dohnanyi SFD with $q \sim -2.7$. This steep SFD goes on to decimate $D > 20$ m objects, leading to $q \sim -1$ 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 $D \sim 1$ km.

Bombardment Model. Next, using our dynamical model, we calculated the collision probabilities and impact velocities between objects in the destabilized population and the giant planet satellites using the methodology of [10]. These data were then combined with the destabilized population's evolving SFD over time. The combination yields the total impact flux on the giant planet satellites over solar system history.

Results. Most sizable satellites have been hit by objects larger than suggested from their basin/crater records (**Fig. 2**). Exceptions may be Iapetus/Hyperion, which are distant enough from Saturn that projectiles experience minimal gravitational focusing. The majority of very large impacts occur early, and they lead to multiple disruption and/or shattering events that reset satellite surfaces and mix surface/interior materials. This heavy bombardment era represents "missing" history, and evidence for its existence might now only be possible via high resolution gravity measurements.

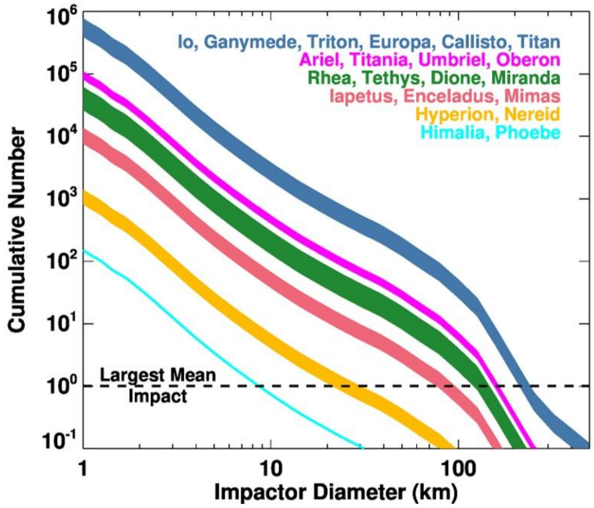

Fig. 2. *Net satellite impacts over solar system history.*

Surface Ages. Recorded history for most satellites begins after the first 100 Myr of bombardment. To quantify this, we computed a crater production model for each satellite. This means choosing an appropriate crater scaling law, an issue where there is considerable debate in the literature. To sidestep this issue, we show model surface ages for several crater scaling laws defined by the parameter *f*, the ratio of crater diameter over projectile diameter.

We show two examples. **Fig. 3** shows our model surface age for Rhea's oldest cratered surface (crater SFD from [8]). We favor values of *f* = 10 because they allow us to reproduce crater SFDs on Ceres [11], a world comparable to Rhea in many respects [12]. Rhea's most ancient surface has an age of *T* = 80 Myr after gas dispersal. Craters in the *T* < 80 Myr epoch were likely erased by large impact resetting events.

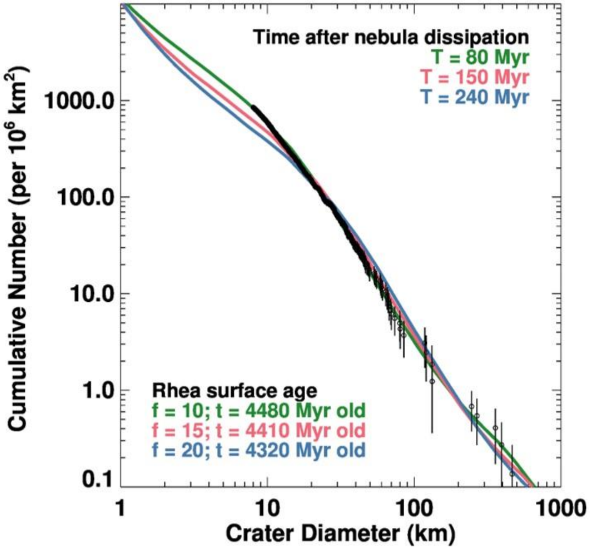

Fig. 3. *Model surface age for oldest Rhea terrains.*

Like Rhea, Mimas also appears to have an ancient surface, regardless of the choice of *f* (**Fig. 4**). Secondary-sesquinary craters likely produce a mismatch between model and data for *D* < 15 km craters [13].

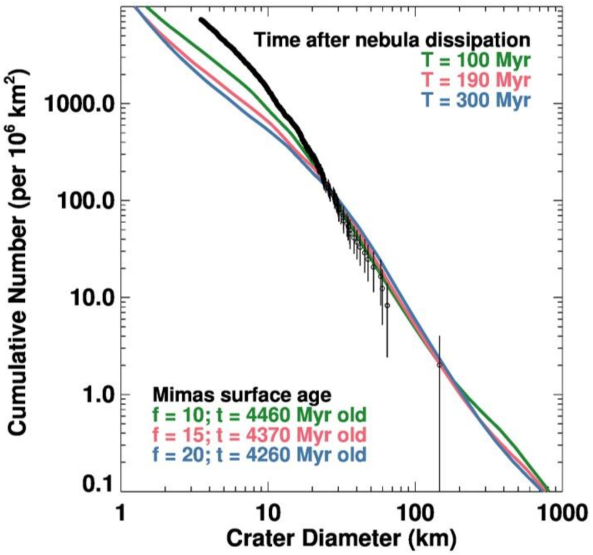

Fig. 4. *Model surface age for oldest Mimas terrains.*

Implications. Most Saturn/Uranus moons have some surfaces as old as those on Mimas/Rhea. This outcome challenges origin models where (i) the moons are very young [1] and (ii) numerous moons were made in succession over many hundreds of Myr from a massive ring [2]. At best, the latter model might only have time to make 1-2 innermost moons (e.g., Mimas).

Our results also raise doubts about whether a Rhea-sized satellite tidally-disrupted over recent times to create Saturn's rings [3]. This putative disrupted world would create a highly-eccentric debris ring that would pummel Saturn's inner satellites. The crater SFDs found on the moons Mimas-Rhea, however, are a good match for impactors coming from the destabilized population (e.g., **Fig. 1; blue curve**).

Conclusions. Most satellites are "missing" their earliest histories. The lost time interval tracks to the most intense period of bombardment, when many satellites were hit by multiple *D* > 100 km impactors.

References. [1] Ćuk, M. et al. 2016. *Astrophys. J.* **820**. 97. [2] Crida, A. & Charnoz, S. 2012. *Science* **338**, 1196. [3] Wisdom, J. et al. 2022. *Science* **377**, 1285. [4] Napier, K. 2022. *BAAS* 54. [5] Nesvorný, D. 2018. *Annu. Rev. Astro. Astrophys*. **56**, 137. [6] Nesvorný, D., 2018. *Nature Astro*. **2**, 878. [7] Morbidelli, A. *et al.* 2009. *Icarus* **204**, 558. [8] Kirchoff, M. & P. Schenk. 2010. *Icarus* 206, 485. [9] Wong, I. & M. Brown. 2015. *Astron. J.* 150, 174 [10] Zahnle, K. *et al.* 2003. *Icarus* **163**, 263. [11] Bottke, W. F. et al. 2020. *Astron. J.* **160,** 14. [12] Schenk, P. et al. 2021. *Icarus* **359**, 114343. [13] Ferguson, S. et al. 2022. *EPSL* **593**, 117652.