THE COLLISIONAL EVOLUTION OF OBJECTS CAPTURED IN THE OUTER ASTEROID BELT DURING THE LATE HEAVY BOMBARDMENT. W. F. Bottke, H. F. Levison, *Southwest Research Institute, 1050 Walnut St, Suite 400, Boulder, CO 80302; bottke@boulder.swri.edu*, A. Morbidelli, *Obs. de la Côte d'Azur, B.P. 4229, 06034 Nice Cedex 4, France*, K. Tsiganis, *Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece*.

Summary. New dynamical models of the lunar late heavy bombardment suggest that numerous comets were implanted in the outer asteroid belt 3.9 Gy ago. Using collisional models, we show this result is consistent with observations.

Introduction. The Nice model [1-3] describes a plausible scenario where the Jovian planets experienced a violent reshuffling event $\sim$ 3.9 Ga. In the Nice model, the Jovian planets are assumed to have formed with a more compact configuration than they have today (all were located between 5-15 AU). Slow planetary migration was induced in the Jovian planets by gravitational interactions with planetesimals leaking out of a $\sim 35 M_\oplus$ planetesimal disk residing between $\sim$ 16-30 AU (i.e., known as the primordial trans-planetary belt). Eventually, after a delay of $\sim$ 600 My ($\sim$ 3.9 Gy ago), Jupiter and Saturn crossed a mutual mean motion resonance. This event triggered a global instability that led to a reorganization of the outer solar system; planets moved, existing small body reservoirs were depleted or eliminated, and new reservoirs were created in distinct locations.

The Nice model is compelling because it can quantitatively explain the orbits of the Jovian planets [1], the orbits of bodies in several different small body reservoirs in the outer solar system (e.g., Trojans of Jupiter [2] and Neptune [1], the Kuiper belt and scattered disk [4], the irregular satellites of the giant planets [5]), and the occurrence of a late heavy bombardment (LHB) on the Moon and other terrestrial planets $\sim$ 3.9 Ga [3,6]. These accomplishments are unique among models of outer solar system formation.

For this abstract, the important ramifications of the Nice model are: (i) Uranus and Neptune entered the primordial disk and scattered comets throughout the solar system, (ii) several mean-motion resonances experienced a temporary transition in character, going from stable to chaotic and then back to stable again, and (iii) the migration of Jupiter and Saturn led to resonances sweeping across much of the inner solar system. This combination led to the capture of comets within the Trojan [2], Hilda [7], and outer main belt regions. Moreover, the captured objects have the same (a, e, i) distribution as the observed D-type asteroids (and related objects) in those zones. This lends some credence to the idea that these objects were implanted 3.9 Gy ago. The problem, however, is that the Nice model also predicts the D-types should dominate these populations. This is true for the Trojans and Hildas [e.g., 8] but not for the outer main belt, whose D-type population is only $\sim 10\%$ of the total (D. Tholen, personal comm.).

To probe this discrepancy, we examined a process missing in the dynamical calculations, namely how the implanted bodies have been affected by impacts over the last 3.9 Gy. Using collisional codes, we argue here that more than 90% of the objects captured in the outer main belt could have been eliminated by impacts. Interestingly, the parameters needed to grind away these objects also produce main belt, Trojan, and Hilda size-frequency distributions (SFDs) that are reasonably consistent with observations. Below we present our work.

Collision Model. To determine whether the captured outer main belt population could have been significantly depleted by collisional evolution over the last 3.9 Gy, we used CoDDEM, a 1-D self-consistent code capable of following the collisional evolution and dynamical depletion of multiple interacting SFDs simultaneously [9]. Here we tracked 5 populations: (1) indigenous inner MB, (2) indigenous outer MB, (3) captured outer MB, (4) Hildas, and (5) Trojans. Each population was also assigned *stable* and *unstable* components according to numerical results [7]:

Stable components. Here *stable* means they have survived a 3.9 Gy dynamical integration. For the main belt SFDs that existed 3.9 Gy ago (pop. 1-2), we assumed they were only 20% larger than the present-day SFDs [see 9]. For the implanted SFDs (pop. 3-5), we assumed their initial SFDs had the same shape as the present-day SFD of the Kuiper belt as determined by [10]. Using the cumulative number $N(>D) \propto D^{-q}$, we assigned $q = 3.25$ for $D > 105$ km and $q = 1.8$ for $D < 105$ km. The size of each SFD was normalized using numerical results from [7] as well as the largest objects in the observed Trojan population. Accordingly, we assumed there was 1 implanted object with $D > 180$ km in the Trojans, 5 in the outer main belt, and 0.4 in the Hildas.

Unstable components. Here *unstable* refers to objects that dynamically diffuse onto planet-crossing orbits over 3.9 Gy. Using results from [7], we set the starting *unstable* pop. 1-5 to 5, 5, 5, 40, and 6 times the size of their respective *stable* component.

The collision probabilities and impact velocities of pop. 1-5 with both themselves and each other were computed from the observed objects or, in the case of the Trojans, were taken from the literature [11]. The representative bulk densities of objects in pop. 1-5 were set to 2.7, 2.0, 0.5, 0.5, and 0.5 g cm^{-3}, respectively. To model individual catastrophic disruption events, we assumed the physical properties of indigenous/ implanted objects were different, with the objects indigenous to the main belt (e.g., ordinary chondrite-like) more difficult to disrupt than the implanted ones (e.g., comet-like). Objects in pop. 1-2 followed the disruption scaling law Q_D^* described in [9]. For pop. 3-5, which are likely dominated by highly porous objects with poorly understood Q_D^* properties, we tested a variety of Q_D^* functions. Our best results came from using $Q_D^* = Q_D^*(\mathrm{ICE})/3$ as defined in [12].

Finally, our constraints include the observed main belt, Hilda, and Trojans SFDs, the contribution of D-type and similar asteroids to these populations, and a host of ancillary data (e.g., asteroid families, asteroid binaries, shock degassing ages among meteorites, micrometeorites reaching Earth).

Results. Assuming that implanted objects are easier to disrupt than indigenous ones (as described above), we find we can reproduce the observed characteristics of pop. 1-5. The evolution of the indigenous/implanted components of the outer main belt over the last 3.9 Gy is shown in **Fig. 1**. Here the SFD of the implanted component drops to values 5-10 times lower than the indigenous component for $D > 40$ km objects. This agrees with the estimated fraction of large D-type asteroids observed in the outer main belt ($\sim 10\%$).

The evolution of the Trojan asteroids, all which were implanted 3.9 Gy ago, is shown in **Fig. 2**. The match between model and observations is surprisingly good. A comparison between the observed and model Hildas (not shown) is not quite as good (i.e., the match is excellent for $D > 40$ km objects, but we predict a factor of a few too many objects for $D < 40$ km), but we consider it reasonable given our uncertainties.

We conclude that if an enormous population of comet-like objects was implanted in the outer main belt 3.9 Gy ago, collisional evolution is capable of eliminating most of the evidence while, at the same time, preserving much of the indigenous main belt and implanted Hilda/Trojan asteroid populations.

Implications. One of the most fascinating and hard to decipher aspects of the main asteroid belt has been the fact that its relatively narrow span (i.e., majority of objects between 2.1-3.3 AU) contains an incredible diversity of compositions that run the gamut from igneous rocks to extremely primitive objects. Previously, it has been argued that the solar nebula had to have experienced radical changes within this zone. Our results instead imply that the diversity in the asteroid belt may be telling us more about the dynamical processes of planet formation than about the intrinsic variation of the solar nebula. In particular, the main belt may be a hideout for all kinds of solar system nomads.

Our work also shows that in order for the Nice model to be correct, some main belt objects must be far easier to disrupt than others. This may help explain the surprisingly young ages and large sizes of several prominent C-complex asteroid families (e.g., Baptistina, Veritas) as well as the plethora of binary asteroids found in the outer main belt. At the same time, however, this would also suggest that many ancient C-complex asteroid families have been rendered unrecognizable over time via collisional grinding. It remains to be seen whether the ages and evolutionary histories of the observed asteroid families are consistent with the predictions of this model.

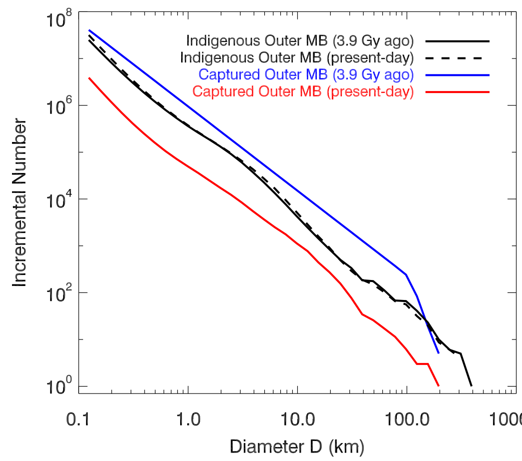

Figure 1: The indigenous and captured component of the outer main belt (2.8-3.8 AU) both 3.9 Gy ago and today according to CoDDEM modeling results.

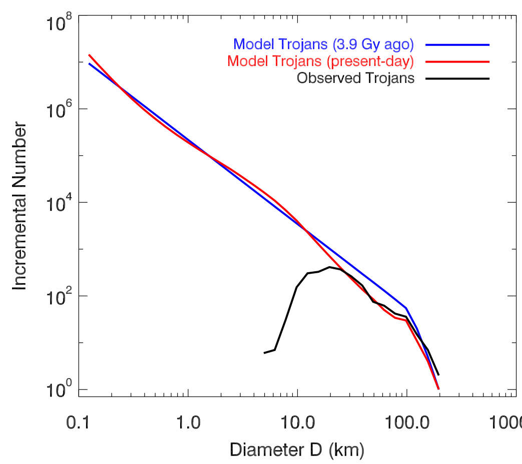

Figure 2: The Trojans asteroids 3.9 Gy ago and today according to CoDDEM modeling results. The black curve is the observed Trojan population.

References. [1] Tsiganis *et al.* (2005) *Nature* **435**, 459. [2] Morbidelli *et al.* (2005) *Nature* **435**, 462. [3] Gomes *et al.* (2005) *Nature* **435**, 466. [4] Levison *et al.* (2008) *Icarus*, in press. [5] Nesvorny *et al.* (2007) *AJ* **133**, 1962. [6] Strom *et al.* (2005) *Science* **309**, 1847. [7] Levison *et al.* (2008), in preparation. [8] Roig *et al.* (2008), *AA*, in press. [9] Bottke *et al.* (2005) *Icarus* **179**, 63. [10] Bernstein *et al.* (2002) *AJ* **128**, 1364. [11] Dahlgren (1998) *AA*, **336**, 1056. [12] Benz and Asphaug (1999) *Icarus* **142**, 5.