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Collisional Evolution of the Edgeworth-Kuiper Belt: Implications for the Origin and Evolution of Small Body Populations

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Abstract. Collisions have been a major process that shaped the Kuiper Belt that we see today. Collisional grinding likely played a significant role in removing mass from the trans-neptunian region and collisions are a mechanism for injecting fragments into resonances to start their journey to become short period comets. The Kuiper Belt preserves the accretional size distribution in bodies $\gtrsim$ 100 km while the size distribution of smaller bodies is the result of collisional evolution. Observational confirmation of the transition size between these different regimes will constrain our understanding of the origin and evolution of the Kuiper Belt.

Collisions and dynamics are the dominant processes that have acted on trans-neptunian material to produce the Edgeworth-Kuiper (E-K) belt that we see today. The realization that collisions occur frequently on the geologic timescale was first pointed out by Stern (1995), while collisional evolution studies spanning the age of the Solar System by Davis and Farinella (1997) noted that primordial E-K populations with masses ranging from a fraction of an Earth mass ($M_\oplus$) to many tens of $M_\oplus$ would collisionally evolve to match the present belt, subject to the constraint that most of the initial mass had to have been in bodies smaller than $\sim$ 50–100 km diameter. Stern and Colwell (1997) found that the primordial E-K belt must have contained considerably more mass, perhaps as much as 100 times more than is found in the E-K belt presently. Davis et al. (2000) showed that a size distribution with most of its mass in small ($\lesssim$ 100 km) bodies was a natural outcome of accretion in the outer Solar System and that collisions would grind down most of the mass. Figure 1 shows the collisional evolution in the so-called classical E-K belt extending from 40 – 48 AU.

The current picture for the history of the E-K belt is one that starts with a much more massive E-K belt than the present one and accretion forms Pluto-sized and perhaps even larger bodies in the trans-neptunian region. Accretion was terminated by a mechanism (or mechanisms) that acted to increase eccentricities and inclinations within the E-K population (see Gladman et al. 2000 for a summary of possible excitation mechanisms). With the "dynamical heating" (increasing eccentricities and inclinations) of the E-K bodies, primarily by Nep-

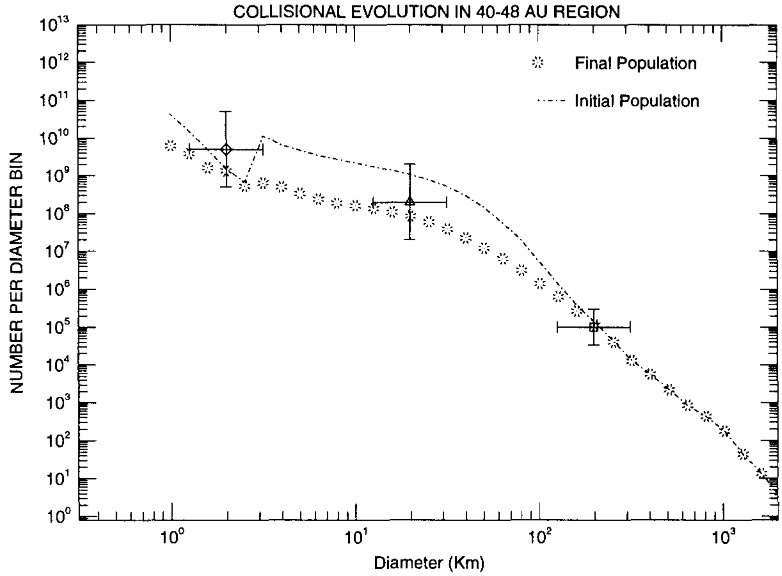

Figure 1. Collisional evolution in the $40 - 48$ AU zone for 3.5 Gyr. The initial mass was $12.5\,M_\oplus$ and the starting size distribution was that at the end of the accretion phase (Fig. 2). Impact velocities were ~ 1 km/s. The dip in population at diameters < 3 km reflects the low degree of fragmentation during the accretion phase.

tune, accretion terminated and collisional erosion began and continues to the present day. The timing of the end of accretion is recorded in the number and size distribution of bodies larger than ~100 km diameter since these bodies are not broken up by subsequent collisional impacts. Figure 2 compares the overall size distribution at various stages of accretion with the inferred size distribution in the present belt (Gladman et al. 1998). As seen here, the model does not satisfy both the slope of the population and the abundance observed in the E-K belt. Either the models are incomplete or other processes have acted to produce the E-K belt that we see today.

Many interesting parallels, and some scientific differences, exist between the main asteroid belt and the E-K belt. Both populations are collisionally evolved, and each must have undergone an accretion phase when the population mass was much larger than that which exists today. The formation of a nearby giant planet – Jupiter for asteroids and Neptune for the E-K belt – was likely the instrument which terminated accretion by stirring up orbits and initiating collisional erosion. In the asteroid case, though, there is direct evidence of collisions, namely the ~25 or so asteroid families (Zappalà et al. 1995) and the detection of asteroidal dust bands which must be collisionally replenished, given the short dynamical lifetime of small particles in the asteroid belt.

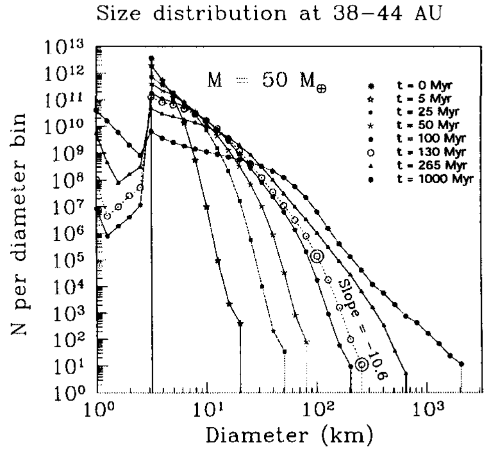

Figure 2. The E-K population at several times during the accretion phase of the population.

For the asteroids, the accretion signature is not apparent. Due to the higher impact speeds in the main belt, bodies as large as ~250 km diameter can be disrupted. There are only 10 bodies larger than that size in the main belt, insufficient to determine the size distribution. Main-belt asteroids smaller than ~150 km are in the collisional regime.

In contrast to the asteroid belt, there appears to be no mechanism other than collisions that could deplete a massive initial population. Direct evidence of collisional processes is lacking at present in the E-K belt. No collisional families have yet been detected (not surprising, given the relatively low number of EKOs, i.e., E-K belt Objects, with good orbits), nor has a dust signature been seen in the E-K belt.

The emerging paradigm for the EKO size distribution has a steep size distribution (power exponent of ~ 4 – 5) in the accretion signature regime ($D \gtrsim 100$ km) and a shallower power law (−3.5) at smaller sizes. That the steep large size distribution will decrease at some size is certain, otherwise the total mass of the E-K belt would be impossibly large. A key observation for the future will be to determine the size at which the slope changes, marking the accretion-fragmentation boundary.

A note of caution is in order. Despite the effort spent on studying asteroid collisional evolution over the past 30 years, a clear understanding of its collisional history has yet to emerge. The asteroid size distribution is known with much greater accuracy (essentially all main-belt asteroids larger than ~ 30 km diameter have been discovered) than is the case for EKOs (only some 300 of the estimated 70,000 EKOs larger than 100 km diameter are now known). The asteroids show considerable structure in their size distribution which cannot be fit by a simple power law or even a two-slope power law function. The "bump" in the size range 100 – 300 km has been interpreted as the signature of the gravity-strength transition (Davis et al. 1979) or as a secondary wave resulting from the strength-gravity transition at a much smaller size (Durda et al. 1998). The scenario for the removal of mass in the E-K belt, namely collisional grinding down to dust which is removed by radiation forces, does not work for the asteroids. The reason for this is the basaltic crust of Vesta which formed very early ($\approx$ 4.54 Gyr ago) and has been preserved throughout the ensuing collisional bombardment. A massive bombardment would have shattered Vesta, mixing its basaltic crust with the abundant diogenitic mantle materials. Hence a small mass initial belt is preferred, in which the total mass in the asteroid belt was a few times that of the present belt at the time that the present dynamical environment was established. An earlier stage, in which much more massive bodies could have been present, cannot be ruled out; such bodies could have been removed by scattering into jovian resonances (Wetherill 1992). Another unresolved issue for asteroids is the so-called "great dunite shortage," i.e., where is the dunite mantle endued from the parent bodies which were collisionally disrupted to expose their metallic cores as the M asteroids? As pointed out by Davis et al. (1999), it is extremely difficult to disrupt and remove all traces of the mantle and crust from the Psyche parent body under the small mass scenario.

Collisional evolution was thought to be well understood following pioneering work by Dohnanyi (1969). However, nature has proven to be surprisingly complex regarding collisional outcomes and Dohnanyi's work is only valid for the special case of self-similar collisional outcomes which is generally not the case for asteroids. It will be of great interest to see what constraints on the collisional history of the E-K belt emerge as we discover more of the distant bodies.

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