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Binary Constraints on Kuiper Belt Collisions

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Summary

The size-frequency distribution (SFD) in the cold classical Kuiper belt (CKB) can be approximated by two idealized power laws: one with steep slope for radii $R > R^*$ and one with shallow slope for $R < R^*$, where $R^* \sim 25$-50 km. Previous works suggested that the SFD roll-over at R^* can be the result of extensive collisional grinding ([5]). Here we use a new code to test the effect of collisions in the Kuiper belt. We find that the observed roll-over could be explained by collisional grinding provided that the initial mass in large bodies was much larger than the one in the present Kuiper belt, and was dynamically depleted. In addition to the size distribution changes, our code also tracks the effects of collisions on binary systems. We find that the extensive collisional grinding required to produce the SFD roll-over at R^* would imply a strong gradient of the binary fraction with R and separation, because it is generally easier to dissolve binaries with small components and/or those with wide orbits. The present observational data do not show such a gradient. This may indicate that the roll-over was *not* produced by disruptive collisions, but is instead a fossil remnant of the KBO formation process.

1. Binary Constraint

The binary KBOs can provide an interesting constraint on the amount of collisional grinding in the Kuiper belt. Recent observations indicate that ∼30% of 100-km-class cold CKBOs are wide binaries ([4]. According to [6], these weakly bound binaries can be disrupted by small, sub-catastrophic collisions with background KBOs which impart kicks on the velocity vector of the binary orbit. Here we used the observed binary fraction in the cold CKB to determine how it limits the amount of collisional grinding in the Kuiper belt. We made different assumptions on the initial state and history of the cold CKB, and the related populations, and identified cases that led to the SFD break of cold CKBOs at $R^* = 25$-50 km. We then evaluated the survival of binary CKBOs in each of these scenarios.

2. Method

Our collisional modeling simulations employ *Boulder*, a new code capable of simulating the collisional fragmentation of multiple planetesimal populations using a statistical particle-in-the-box approach ([2]). It was constructed along the lines of other published codes. A binary module was inserted in the *Boulder* code. As the population of impactors evolves with time due to collisional fragmentation, the code calculates the time-dependent rate of change of binary orbits, and evolves them according to the procedure described in [3]. The binary system is assumed to become dissolved either if eccentricity $e > 1$, or if the semimajor axis exceeds the Hill radius.

3. Results

We considered both the pre-Late Heavy Bombardment (pre-LHB) and post-LHB epochs. We found that the total mass loss due to the collisional grinding of KBOs after LHB is only ∼15% in the CKB and ∼5% in the scattered disk. This shows that the SFD may remained essentially constant since the LHB. For the pre-LHB phase, we confirm the results of [1] who found that, to produce the roll-over at $R^* = 25$-50 km, the initial mass in large CKBOs must have been much larger than it is now. The best results were obtained with the initial mass between 7 and 15 $M_{\rm Earth}$ (Fig. 1a). A reasonably conservative lower limit on the initial disk's mass is ∼1 $M_{\rm Earth}$ ([3]). As the disk mass is reduced only by a factor of ∼10 by collisional grinding, additional depletion by dynamical processes would be required to reach the estimated current mass (∼0.01 $M_{\rm Earth}$).

We now consider the binary survival (Fig. 1b). There is a clear trend with the physical size of binary components. Specifically, more than 50% of binaries

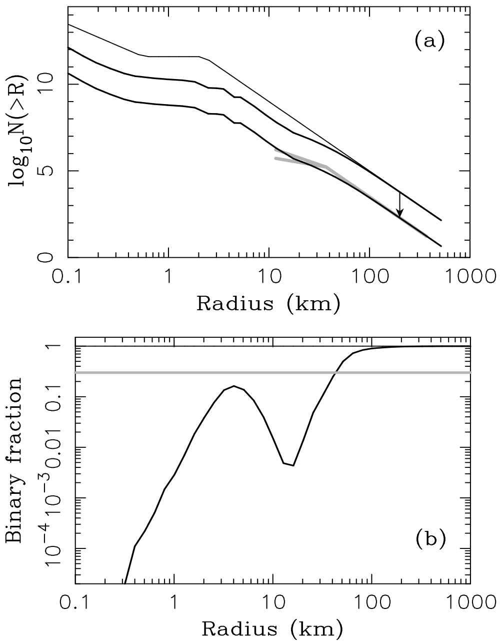

Figure 1: (a) SFD evolution and (b) binary survival before LHB for the initial SFD shape used by [1]. The thin black line in (a) shows the initial SFD. The middle bold black line in (a) shows the final state after 600 Myr of collisional grinding. The bottom bold black line in (a) shows the SFD after a dynamical depletion factor of 30 was applied to the final distribution (change indicated by an arrow). The bold gray lines in (a) denote observational constraints on the present SFD in cold CKB. The bold gray line in (b) marks the binary fraction of 0.3. We assumed that the initial binary fraction was 1. The bold black line in (b) shows the expected binary fraction in this model. The binary separation was set to 0.01 Hill radius.

with radii $R > 50$ km survive, while the survival rate for $R = 10$-20 km is only ∼0.5%. The trend is reversed for $R < 10$ km because of the lack of small impactors with $R \sim 0.5$ km that could unbind binaries with $R \sim 5$ km (Fig. 1a). These results are generic. If the parameters were set up so that collisional grinding produced the SFD roll-over of cold CKB at $R^* = 25$-50 km, the final binary fraction showed a strong gradient with radius.

Figure 2 shows the observed fraction of binaries in the cold CKB ([4]). It does not show any strong gradient with R. Instead, the observed binary fraction is relatively constant and large down to the smallest surveyed objects ($R \sim 30$ km). We therefore believe that the existing data are not suggestive of the kind of trends that we would expect to see in a population that experienced strong collisional grinding. This may indicate that the SFD roll-over in the cold CKB at $R^* = 25$-50 km was not produced by disruptive collisions, but was instead already in place when KBOs were forming. Better observational statistics will be needed, especially for $R \leq 30$ km, to test this preliminary conclusion.

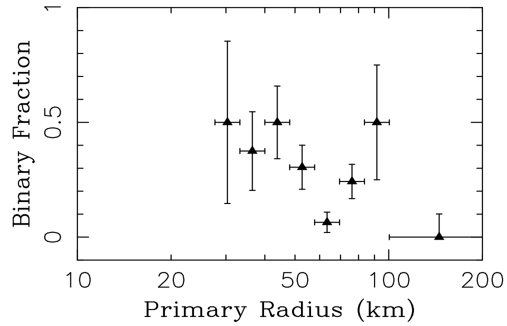

Figure 2: The binary fraction in the cold CKB as a function of primary radius. Data for 122 KBOs with low inclinations, including 33 binaries, were taken from the observational surveys described in [4], and crudely debiased (see [3]). The error bars and upper limits of non-detections show formal 1-sigma uncertainties.

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