ASTEROID COLLISIONAL EVOLUTION: IMPLICATIONS FOR INTERNAL STRUCTURE.
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A new model of asteroid collisional evolution is developed, based upon the well-known Dohnanyi [1] formalism and upon scale-dependent collision and fragmentation physics using the prescription suggested by Cheng [2]. The model is constrained by a size distribution inferred from crater size distributions on the Moon, Mercury and Mars, which are known to be remarkably similar from prior work [3], and which is assumed to apply at the end of the massive early bombardment, 3.9 Gy ago. The asteroid size distribution is constrained to evolve over 3.9 Gy from this condition to the present day size distribution as inferred from observation. In this evolution model, the survival of a basaltic crust on Vesta can be accommodated, together with formation of >100 exposed metal cores. The new evolution model has the property of convergence toward an equilibrium state, forgetting the details of the initial state except at the largest sizes, although the collisional equilibrium state is not a simple power law. To fit observational constraints, the new collisional model suggests that asteroid fragmentation is not described by a simple Weibull flaw distribution with self-gravity strengthening, but that asteroids of about 10 km size are stronger than such a fragmentation law would predict. This may result from parent body geologic processes. The model predicts that the asteroid population from about 1 to about 200 km size, 3.9 Gy ago, was only a few times larger than today, and it predicts the size distribution below 1 km size to be shallower than the Dohnanyi index 2.5 power law.

Cheng [2] has previously investigated the collisional state of the main belt, where the relative importance of erosion, destruction, and fragmentation processes can be evaluated versus asteroid size, using the observed size distribution and including recent theoretical under-standing of size-dependent collisional outcomes. The fundamental picture is based on the Dohnanyi [1] model of a collisional asteroid belt, which predicted the well known power law cumulative size distribution with index 2.5, or

$$N(D) \propto D^{-2.5} \qquad (1)$$

where N(D) is the cumulative number of asteroids larger than mean diameter *D*. The Dohnanyi model considered the competition between three processes governing evolution of the number of asteroids in a given size range: erosion caused by impacts of small enough impactors that ejecta are released and the target may be shattered, but not dispersed; destruction by collisions with large enough impactors that do fragment and disperse the target; and finally fragmentation when collisional fragments are created in the size range of interest. Dohnanyi found that in an analytical approximation, the "kinetic equation" governing the evolution of the size distribution had a self-similar solution, in which the distribution tended toward an index 2.5 power law.

Cheng [2] found that with size-dependent collision physics, there could be a transition size of typically 5 km, where for smaller asteroids the rates of destruction by catastrophic break-up and creation by fragmentation of larger asteroids could be balanced; whereas for larger asteroids the rate of collisional destruction was dominant over fragment creation and erosion. It was speculated that below the transition size, most asteroids should be products of catastrophic disruptions, and that asteroid families should become hard to identify. However, Cheng [2] did not actually construct collisional evolution models such as reviewed by Davis et al. [4].

The present work extends the formalism of [2] to derive a new asteroid collisional evolution model and constrain it with observations. It is found that the collisional state evolves toward an equilibrium in which the overall loss and creation rates are balanced, as was found by Dohnanyi [1], but only below a transition size ~4 km. This equilibrium state is no longer self-similar, and for larger sizes the losses overall dominate the creation rate. Also the evolution time at the largest sizes exceeds the age of the solar system, so the collisional equilibrium is fully attained only at sufficiently small size.

Previous work reviewed by Davis et al. [4] has used asteroid collisional evolution models, constrained by the present asteroid size distribution, to infer information on asteroid fragmentation, meaning the condition under which catastrophic fragmentation occurs. This is conventionally parameterized by the specific energy *Q**, which is the kinetic energy per unit target mass required for destruction of the target, and which is a function of the diameter *D* of the target. Durda et al. [5] found that the present size distribution was best fitted by a *Q*(D)* which had, on the one hand, extremely weak asteroids overall, and on the other hand steeper scaling of *Q** with *D* than would be expected in both the strength-dominated and gravity-dominated regimes. As reviewed by Asphaug et al. [6], this was both the lowest overall *Q** and steepest scaling among several theoretical models which collectively spanned two orders of magnitude in the predicted value of *Q**. Another uncertainty arises from the assumed initial state of the asteroid population; Durda et al. [5] assumed an initial population with 6 times the present main-belt mass and an index 2.5 power law. More recently, W. Bottke and collaborators (private communication) have revisited the problem and have applied new observational constraints (such as the survival of Vesta with a basaltic crust and one giant crater, and the number of family-forming events for D > 100 km), concluding that the best fit $Q*$ was close to the theoretical consensus proposed by Asphaug et al. [6]. This consensus form for $Q*$ is also close to the nominal case assumed by Cheng [2].

The difficulty in previous work has been that the collisional evolution models are inadequately constrained by observations. Although the final state must match the present size distribution, both the initial state and the asteroid fragmentation law as parameterized by $Q*(D)$ are unknown or poorly constrained. Essentially, there are two unknown functions, but only one evolution equation for the size distribution. Without additional constraints, the evolution of the size distribution can yield only qualitative inferences.

The present work will impose a significant additional constraint on the temporal evolution of the size distribution, by requiring the model to fit not only the present size distribution, but also a specified size distribution at the end of the late heavy bombardment of the Moon, 3.9 Gy ago. Specifying the size distribution at an initial state as well as a final state essentially removes one of the unknown functions for the evolution model, and allows estimation of the other unknown function, which is $Q*(D)$.

It is well-known that the ancient cratered highlands of Moon, Mercury and Mars all have similar crater size distributions [3], and it is widely thought that the crater size distributions, particularly on the lunar highlands, are close to the initial production functions. When the crater size distributions are expressed in terms of so-called R-plots (the ratio between the differential size distribution dN/dD and the function D^{-3}, plotted vs. D on logarithmic scales), then the R-plots for Moon, Mars and Mercury are consistent with the velocity differences expected for a single population of impactors within the inner solar system (higher impact velocities for lower heliocentric distance). This impactor population is identified with that responsible for the late heavy bombardment or LHB [3], which is known from Apollo samples to have ended about 3.9 Gya.

The present work adopts the interpretation that the crater size distributions from the highlands of Moon, Mars, and Mercury indicate a single impactor population at the end of the LHB, and that the impactor size distribution constrains the asteroid size distribution at that time. The kinetic equation [2] for the size distribution is then evolved forward in time, starting from the assumed initial condition at -3.9 Gya from [3] and continuing to the present epoch, where the size distribution is assumed to be that from Fig. 4, ref. [2].

An example of a model which evolves between the specified initial and final states is shown in Fig. 1. The model agrees with data at the present epoch within observational uncertainty. The model predicts the slope of the size distribution at small size << 1 km to be shallower than the Dohnanyi index 2.5 power law. The form of $Q*$ is unexpected; it appears that asteroids around 10 km size must be harder to disperse than predicted by [6]. There may be evidence for strength features of this scale on Eros and Mathilde [7]. Models with the consensus form [2, 6] of $Q*$ do not appear to fit the data.

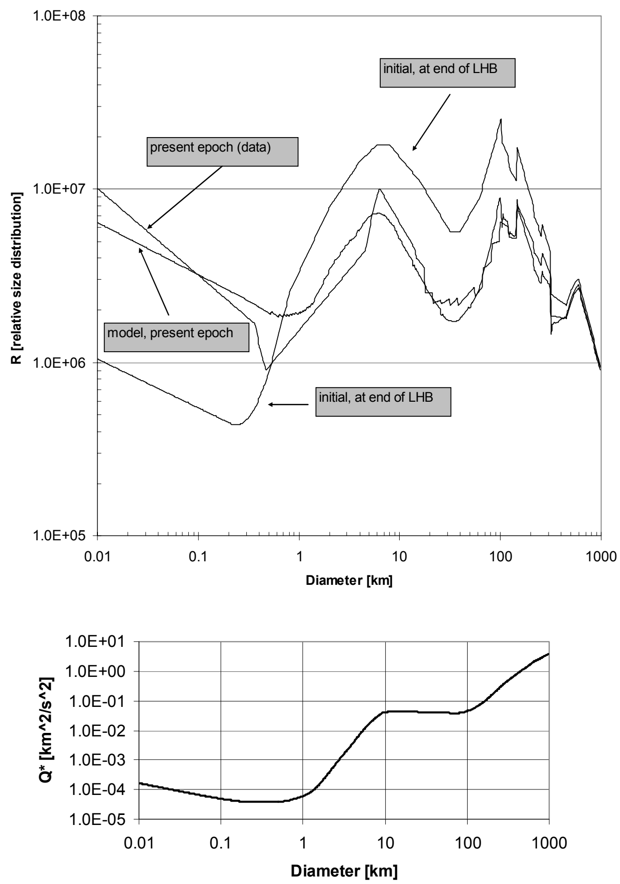

Fig. 1. (upper) R-plots for initial state at end of the LHB, data at present epoch from [2], and collisional evolution model at present epoch. **(lower)** assumed $Q*$

References: [1] Dohnanyi, J. 1969, *JGR, 74*, 2531; [2] Cheng, A. 2004, *Icarus*, *169*, 357; [3] Strom, R. and Neukum, G. 1988, in *Mercury*, ed. F. Vilas et al., 336; [4] Davis, D. et al. 2002 in *Asteroids III,* ed. W. Bottke et al., 549; [5] Durda, D. et al. 1998. *Icarus*, *135*, 431 ; [6] Asphaug E. et al. in *Asteroids III,* ed. W. Bottke et al., 463. [7] Cheng, A. in *Asteroids III*, ed. W. Bottke et al. 351.