NEW FINDINGS FROM SIMULATIONS OF THE HISTORY OF MAIN BELT ASTEROIDS.

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Introduction: This is a synopsis of a study [1] of the histories of the asteroids in the main asteroid belt. That history is one of multitudes of collisions. The consequences of those collisions are cratering, erosion, spin, fragmentation, binaries, wobblers and occasional catastrophic disruption and dispersion of the asteroids.

Extensive information for asteroid orbits, sizes, shapes, composition, and rotation rates of those asteroids is now available. Those result from their history; but to interpret how those lead to the preset state requires understanding the processes. That understanding can be improved by simulations of the histories.

I have combined current models, a Monte Carlo method, and a new code *"SSAH"* for stochastic simulations of histories of the main belt. The results lead to important new findings about asteroid histories, including the distribution of spins; the (non) role of strength in spin limits; the 'unusual' spins of 2001 OE84; and of large slow-spinning tumbling objects (Mathilde); the "V-shape" in the spin versus diameter plot; the non-Maxwellian distribution of spins of a given diameter range; the numbers of expected binaries and of expected tumblers, and more. At the same time, the simulations expose some gaps in our knowledge that require further research.

Background: A number of researchers have developed models of the history of the asteroids in the main belt. Dohnanyi, 1969, [2], was the first to develop a collisional evolution model. His focus was on the evolution of the population-size distribution of the belt; and especially on conditions for which that distribution is invariant in time. Since that time others have followed his lead. But they did not include modeling of the spin histories. That omission has been noted. Very recently Chang et al., 2019 [3] stated: "a comprehensive simulation on the spin-rate evolution for the entire main asteroid belt is needed …". That is the subject of this research.

Models: The models include those for all outcomes of impacts for the range of condition in the main belt: erosion, cratering in a half-space, cratering on a finite target, catastrophic dispersions, fragmentation, spins, binaries and tumblers. These are models developed in the last two decades, and many of them based upon the point-source approximation for hypervelocity impacts developed by Holsapple and Schmidt [4]. Space limitations here preclude any meaningful presentations of the details of the required models. One can consult [1] for those details.

The Simulations: A *SSAH* code simulation uses a user-chosen set of asteroid targets, with a chosen definition of the main belt population to define the impactors. Those, and all other problem parameters, are chosen by the user in a graphical input panel. A set of 10 'knobs' allow modifications to the models for those that are not well-determined. Different types of studies are based upon different choices for the target asteroids.

Each target asteroid is struck by a large number of other asteroids at random surface locations, and angles and velocities. The numbers of of impacts is determined by the density and velocities of the impactor population. For each impact material is eroded: removed by cratering and ejecta processes, thereby decreasing its size. Depending upon the geometry of the impact, and the efficiency of the transfer of that impactor's angular momentum to the target, each impact will change its spin vector and wobble (non-principal axis spin). On average, the spin is increased. Between impacts, the wobble decays as a result of internal dissipation. If the spin increases to a value above the gravity limit, an adjustment of shape or size is assumed which reduces the excess spin to or below the gravity limit.

That process continues until an impact large enough to destroy (pulverize) the target might happen. That happens many times for a small target (see events table) but never for one that is sufficiently large. When pulverized, the target is replaced at its original diameter and a random reset spin (see below). That cycle is repeated over the time intervals between pulverizations.

SSAH calculates the time histories of those test asteroids using time-steps usually over, according to the choice of the user, the epoch of the solar system. It uses stochastic measures for all of the parameters defining the sample asteroid, for the geometry of the impacts, and for each impactor's properties.

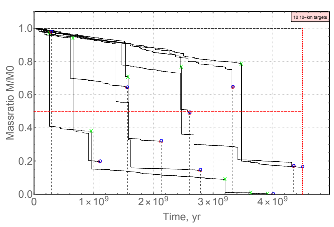
A typical simulation has over 17,000 target asteroids that have a defined spin in the 2019 spin data-base [5]. The number of impacts for each one depends upon its size and upon the smallest impactor that is considered. Those numbers are determined by the *intrinsic collusion probability* in the main belt. For example, each 1 km S-Type object is struck by objects 2.5 m or larger (those having 1% or more of the energy required to catastrophically disperse them) on the order of 4000 times over the age of the Solar System. (See events table). *SSAH* accounts for the large number of impacts of each target by using a novel explicit-implicit approach which calculates explicit detailed results for each of a large number of the largest impactors and average results for the remainder. All impact models are defined in separate functions in *SSAH*, which allows easy modification for testing or if newer or better models are developed.

The most important special case is reported here: it assumes that the population of the main belt is steady in time, although *SSAH* also has the capability to model time-varying populations. For a steady population of impactors, fragments from larger impacts replace those lost by dynamic processes. In that case the result does not depend upon fragmentation nor dynamic depletion models, neither of which is well defined.

Results: The primary results are the histories of erosion and of spin for the designated targets and their interpretations. The simulations also provide important new insights into many secondary features including the role of physical spin limits, the formation of tops and binaries, the lifetimes, tumbling, crater counts and family formation. Those and others are presented in a set of 15 output plots, many of which are user adjustable after the simulations are complete. A comparison of the outcomes to the data of the database allows one to judge the fidelity of the models.

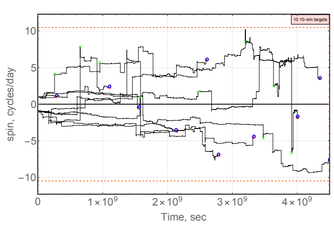
A sampling of results is as follows:

1. Erosion histories:



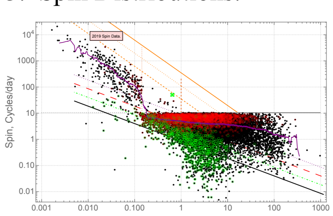
Mass histories for a set of ten initially 10 km asteroids. Only one survives 4.5 Byr. Each suffers several large impacts.

2. Spin Histories:



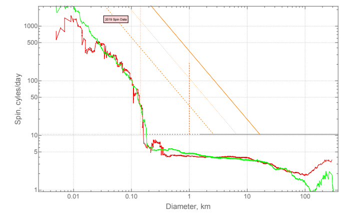
Spin histories for 10 asteroids with initial diameters of 10 km. None reach the red gravity spin limits.

3. Spin Distributions:



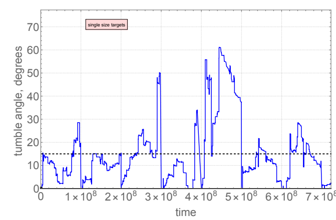
The final spins of the ~17,000 objects of the 2019 spin database. There are 16% gravity limit events (possible binaries), and 4.6% tumbling objects.

4. Running box mean spins:



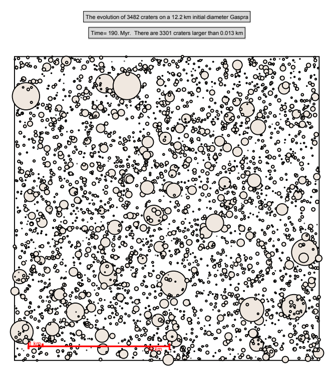
A comparison of the running box means of the simulation (green) with that of the data (red). Differences are only apparent for the smallest and largest sizes.

5. Wobbling and Tumbling:



The wobble angle history of a 5 km asteroid over 700 Myr. The vertical jumps are due to impacts, the sloped portions are a dissipative decay.

6. Asteroid cratering



The cratered surface of Gaspra from a simulation of a 190 Myr history. The largest craters are 2-3 km. This is the final frame of a movie available at Gaspra Cratering Simulation Movie.

An assessment of these and further results are given in [1].

The code *SSAH* (requires *Mathematica*) and supporting files are available at SSAH Download.

References:

[1] Holsapple (2021) arXiv:2012.15300 [astro-ph.EP].
[2] Dohnanyi, J.S., (1969). J. Geophys. Res. 74, 2531.
[3] Chang, C.-K.,et al. (2019) ApJS 241, 6.
[4] Holsapple, K.A., Schmidt, R.M., (1987). J. Geophys. Res.92, 6350–6376.
[5] Warner, B., Pravec, P., Harris, A. (2018). Asteroid Lightcurve Database (LCDB) V2.0. NASA Planetary Data System 304.