FORMATION OF LARGE MULTI-ASTEROID SYSTEMS THROUGH SUB-CATASTROPHIC IMPACTS.
R.-L. Ballouz, K. J. Walsh, H. F. Agrusa, and M. Jutzi.
1Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, 2Southwest Research Institute, Boulder, CO, USA, 3Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France, 4University of Bern, Bern, Switzerland.

Introduction: Large main belt asteroids with diameters greater than approximately 100 km are likely remnant planetesimals formed from accretionary processes in the early Solar System [1,2]. Collisional grinding of this population leads to the formation of asteroid families, observations of which provide an understanding of the formation and evolution of the inner Solar System (e.g., [3]). A subset of these large asteroids is found to be in multi-asteroid systems: asteroids with one or more satellites. The formation of these large multi-asteroid systems is generally thought to occur through the catastrophic disruption of a parent body (e.g., [4]), in a similar fashion to asteroid family formation. Other plausible multi-asteroid formation mechanisms operate far too slowly for large main belt asteroids [5]. Combined with quantitative constraints on the physical properties of the primary through measurements of system orbital properties (e.g., [6]) and direct imaging [7], multi-asteroid systems represent a natural laboratory for studying collisional history of large leftover planetesimals in detail.

Here, we study the mechanics of multi-asteroid system formation using numerical simulations of sub-catastrophic collisions, in light of recent observations of these systems that have provided detailed constraints of their spin and shape properties. We find that stable satellites are sourced from a collisionally-generated debris tail that is torqued to periapse distances, q > 1 primary radius, R (Fig. 1). Consistent with observational constraints [7], we find that collisions that result in fast-spinning and elongated primaries generate a larger mass of temporary satellites. Subsequent dynamical evolution of the system enables a fraction of these satellites to remain stable for long timescales.

Observational constraints for formation scenarios of multiple asteroid systems: In the past, theoretical studies of multi-asteroid collisional formation and dynamical evolution have been limited by the paucity of known large multi-asteroid system and the relatively poor constraints into their physical properties. However, recent advancements in telescopic capabilities and observation techniques, such as adaptive optics [7], have provided a new view of large multi-asteroid systems. The main constraints we consider for large multi-asteroid systems are: (i) primaries have rotation periods 5-6 h, which is significantly more rapid than the 10 h spin period of the average large main belt asteroid, (ii) primaries are more elongated than average as indicated by light curve amplitudes and direct imaging, (iii) multi-asteroid systems are predominantly C-complex systems, with no known S-complex multi-asteroid system. Previous numerical modeling has found that satellite formation is possible in large collisions between asteroids, but these models did not track the shape and spin of remnant bodies [4]. Therefore, the relationship between successful satellite formation and remnant spin and shape haven't been previously leveraged for understanding the key mechanisms at work. Are the shape and spin of the primary indicative of specific impact scenario that preferentially produces satellites (e.g. oblique impacts)? Or, is rapid pre-impact rotation essential for satellite formation?

Figure 1. Example of numerical simulation of a sub-catastrophic impact on to a 100-km asteroid, resulting in the formation of stable satellites with q/R > 1 (blue particles in a-f, and blue curves showing orbits in f).

Modeling approach: To model the shape and spin outcomes following a sub-catastrophic collision on to a 100-km asteroid, we use a handoff routine between Smoothed Particle Hydrodynamics (SPH) code that models the impact and shock propagation [8] to an N-body code, pkdgrav, that handles the gravitational reaccumulation and granular mechanics that determine its final shape and spin [9]. We have implemented updates to the handoff to simulate the effect of a rotating target. This allows a wide-ranging and rapid assessment of pre-impact rotation on impact outcomes.

We model impacts that are typical of those experienced by large asteroids in the Main Asteroid Belt, with impact speeds of 5 km/s over a range of impact angles from 0–75° by 5–18 km-radius impactors onto 100-km targets, resulting in approximately 50–99% of the total mass returning to the largest remnant. The SPH model is specific to primitive (low-albedo, low density) asteroids with compaction as a key physical process [Jutzi et al. 2019]. The density of each simulated particle is approximately 2 g/cm³, resulting in bulk densities around ~1.3g/cm³ which is typical of dark C-
complex asteroids [10]. Targets with pre-impact spin had periods of 2.5–10 h. We simulated approximately 50 cases for simulation times of ~40 h, which was sufficient to ascertain the stability of newly formed satellites through a handful of orbits about the primary. Satellite long-term stability was also studied, and will be reported on in a forthcoming publication.

**Results:** The formation of multi-asteroid system is sensitive to pre-impact rotation and the angle of impact, where a typical high angular momentum system is shown in Fig. 1. There is an initial asymmetric ejecta cloud and the bulk of the primary body is immediately distorted into an elongated shape. In Fig. 1, a 26 km impactor impacts a 100km target with a 3 h rotation period at a 60° angle at 5km/s. Due to the high angular momentum, the primary is distorted and a tail of debris is generated that trails the rotation of the primary and clumps into discrete remnants. The formation of this tail of debris is reminiscent of Moon-forming simulations through giant impacts on to Earth [11].

Fig. 2 summarizes the outcomes of the numerical simulations. At the end of each simulation (~40 h post-impact), we calculate the primary physical properties and the mass of satellites with \( q > 1.5 \). In Fig. 2a, we show that the mass of satellites normalized by the primary mass can be predicted by the specific impact energy, \( Q \), of the collision normalized by a rotation-dependent catastrophic disruption threshold [12, 13]. Furthermore, our simulations reproduce observations of the large primaries in multi-asteroid systems. Specifically, we find that more elongated primaries, as quantified by the ratio of their minor to major axis (\( c/a \)), tend to have more mass in orbit (Fig. 2b), and these primaries also tend to have faster post-impact spins (Fig. 2c). Remarkably, we see a sharp transition in the incidence of primaries with satellites at post-impact spin periods of 10 h or less, matching observations.

**Outlook:** Sub-catastrophic collisions onto 100-km asteroids result in the formation of temporary satellites in orbits that are stable in the short term. These impacts can place up to 10% of the target mass into orbit around the primary, with the total mass being enhanced for fast rotating targets that are hit at high impact angles. Scenarios that lead to a large mass fraction in orbit about the primary also lead to faster rotating and elongated post-impact primaries, as seen in observations. We have conducted N-body simulations that show the long-term stability (>>1yr) of these initial satellites and its dependency on shape and spin properties, which we will present in a forthcoming publication.

**Acknowledgments:** This material is based on work supported by NASA under Contract 80NSSC22K0045 issued through the Solar System Workings Program. H.F.A. was supported by the French government, through the UCA J.E.D.I. Investments in the Future project managed by the National Research Agency (ANR) with the reference number ANR-15-IDEX-01.


![Figure 2](image-url)