# Asteroid spin-up fission systems

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Among asteroids smaller than about 15 km in diameter, there is a population of binary and multiple asteroid systems that show characteristics strongly suggesting their formation by spin-up fission. I will review the current observational data we have on the systems and compare them with predictions from theories of formation of asteroid systems. I will show that the best explanation of their observed properties is provided by the theory of fission of cohesionless (rubble-pile) asteroids spun up to the critical spin frequency by the YORP effect.

Observed asteroid systems are of two kinds: bound and unbound. Bound asteroid systems typically consist of a larger primary and one or two smaller satellites. Unbound systems consist of two asteroids orbiting the Sun on highly similar orbits, again with one being typically larger (primary) and the other being smaller (secondary). These two groups are not exclusive; there exist systems with one or two bound and an unbound secondary.

Our current sample consists of 133 bound asteroid systems (binaries or triples) with primary sizes between 0.12 and 13 km and of 178 asteroid pairs with similar primary sizes. Bound systems have been observed in heliocentric orbits from near the Earth to the outer main belt, while asteroid pairs are recognizable only in the main belt where their orbits are only slowly dispersed so the pairs can be identified for up to 2 Myr after formation.

The leading observational techniques for discovery and characterization of asteroid systems are radar imagery (for near-Earth asteroid systems) and lightcurve photometry (for main-belt ones).

The observed characteristics of asteroid systems suggesting their formation by rotational fission of parent rubble-pile asteroids after being spun up by the YORP effect are as follows. The angular momentum content of binary asteroids is close to critical. The orientations of satellite orbits are non-random; the orbital poles concentrate near the obliquities of 0 and 180 degrees, i.e., near the YORP asymptotic states. The spin rates of primaries of asteroid pairs (unbound systems) are correlated with the secondary-to-primary size ratio; the primaries of pairs with small secondaries rotate at frequencies close to critical, but pairs with larger secondaries have slower primary rotations as a large part of the rotational angular momentum was carried away by the escaped secondary. Relative velocities of the components of asteroid pairs at the time of formation were low, on an order of the escape velocity from the parent body, indicating a gentle push in their formation. There has not been observed any secondary orbiting its primary below the Roche limit for strengthless bodies, consistent with their rubble-pile structure. The shapes of primaries of systems with bound secondaries are nearly spheroidal and they show an equatorial ridge in the highest-resolution radar shape models. The satellite orbits in close binary or triple systems have low inclinations to the primary's equator and the spin states of asteroid pair primaries are close to principal-axis rotation, as expected for material forming the secondary pulled away by the centrifugal force.

While the observational data support the theory of formation of small asteroid systems by YORP-induced rotational fission, details of the formation process and evolutionary paths are lacking. I will also mention a few anomalies we have observed. The most striking anomaly is that there are two systems with super-critical angular momentum content, (4951) Iwamoto and (32039) 2000 $JO_{23}$, which require explanation.

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