Depletion and excitation of the asteroid belt by migrating planets

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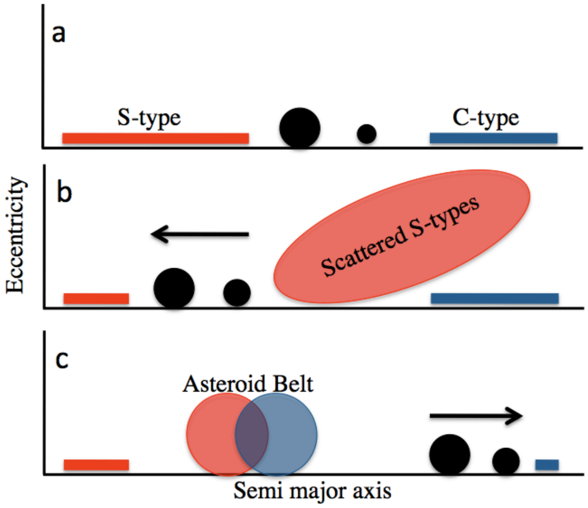
Abstract

The excitation and depletion of the asteroid belt has historically been modelled with stranded planetary embryos or resonance sweeping caused by the dissipation of the solar nebular gas. Both of these methods rely on the asteroids, with their substantial diversity, being "born" largely where they are found today. We present a model of early inner solar system evolution whereby the gas migration of Jupiter and Saturn bring them to 1.5 AU, truncating the disk of planetesimals, before they migrate outward to their current locations. This model, dubbed "The Grand Tack", solves some outstanding problems, including the size of Mars, and has implications for the excitation, depletion and origin of the asteroid belt.



The Grand Tack

Giant planets in gaseous protoplanetary disks carve annular gaps in the disk and migrate inward in a process called type II migration. However, this evolution is very different for two planets in resonance. For Jupiter and Saturn, hydrodynamic simulations show that Saturn is eventually captured in the 2:3 mean motion resonance with Jupiter [1]. This configuration leads to a change in the net torques felt by the planets and a migration reversal, with both planets migrating outwards instead of inwards. This evolution persists while the planets remain in resonance until the disappearance of the gas disk. If Jupiter migrated in to 1.5 AU before reversing its migration, the inner disk of planetesimals and embryos would have been truncated at 1 AU, leading to initial conditions for terrestrial planet formation that reproduce all four terrestrial planets including Mars [2,3]. The question then becomes the fate of the asteroid belt after the planets migration.

Our simulations begin with two entirely separate parent populations of asteroids (Fig. 1). First, there is the planetesimal disk interior to Jupiter, from $\sim$0.7 AU out to 3.0 AU, determined by Jupiter's starting location - nominally set at 3.5 AU by estimates of the snow line location [4]. Between and beyond the giant planets is a second population of asteroids. We label the inner population "S-types" and the outer "C-types", however compositional variations across each is expected.

During Jupiter's inward migration it scatters about $\sim$15% of the planetesimals from the inner disk (the "S-types") onto orbits beyond 3 AU. When Jupiter and Saturn "tack" and begin their outward migration, they first encounter this scattered population of S-type material and only later begin encountering the "C-type" bodies that are initially located between and beyond the giant planets. We find that a fraction (0.5%) of the "S-type" material is scattered back inward, ending on stable orbits in the asteroid belt. A similar fraction of the "C-type" material also reaches stable orbits in the asteroid belt.

The final asteroid belt in our simulations is composed of material from both populations: we reproduce the observation that S-type material dominates the inner belt (interior to 2.8 AU) and that C-type material dominates the outer belt. Eccentricities are elevated among our final implanted asteroids, but are likely to be re-shuffled during the later events that occur during the so-called Late Heavy Bombardment. The inclinations, which are less susceptible to later changes, cover a range of 0–20°, appropriate to match the asteroid's distribution when later Solar System evolution is accounted for [5].

References

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