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The asteroid belt and Mars' small mass explained by large-scale gas-driven migration of Jupiter

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Abstract

Dynamical simulations of terrestrial planet accretion consistently fail to produce reasonable Mars analogs; planets at Mars' orbital distance are systematically too massive [1]. A recent model, dubbed the "Grand Tack", has found that the inward migration of Jupiter to 1.5 AU, and its subsequent outward migration, can explain the small mass of Mars [2, 3]. This migration, described below, must have occurred while the gas disk was still present, during the first 3-10 Myr of solar system evolution.

The asteroid belt is a first-order constraint for this model, as its survival and structure must be accounted for after the migration of the giant planets. The work we present provides an explanation for the compositional and orbital structure of the asteroid belt as the result of Jupiter and Saturn scattering bodies from two different source populations onto stable orbits in the asteroid belt.

1. Giant planet migration

Giant planets in gaseous protoplanetary disks carve annular gaps in the disk and migrate inward in a process called type II migration. However, the 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 [4]. 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. Thus, Jupiter could have migrated inward only before Saturn approached its final mass and was captured in resonance.

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]. Given that Jupiter probably formed at several AU or more, a critical constraint on the viability of this scenario is the existence of present-day asteroid belt between 2.0–3.2 AU, as the migration of Jupiter to 1.5 AU would seemingly empty that region of material.

Here we will present results from our migration scenario. The scenario is backed up by a larger exploration of parameter space that embraces many possibilities, demonstrating the robustness of the results [3]. Throughout we maintain the fundamental assumption that Jupiter "tacked" at 1.5 AU. Our nominal scenario is depicted in Figure 1., where Jupiter begins at 3.5 AU, and migrates inward to 1.5 AU. At this point Saturn has grown to its full mass, triggering the migration reversal, allowing both planets to migrate outwards toward their final resting places.

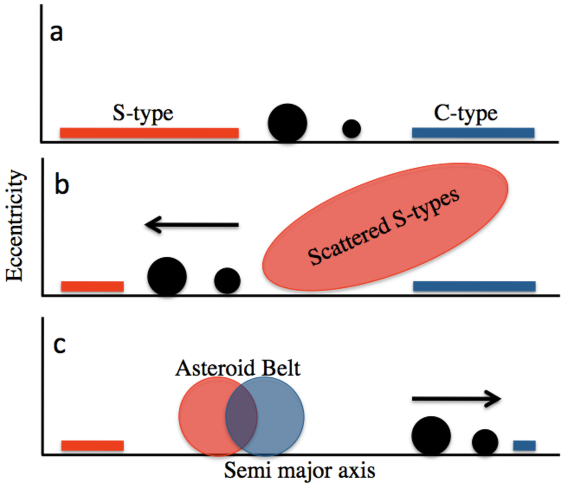

Figure 1: Diagram of the proposed "Grand Tack" scenario.

2. Constraints from the asteroid belt

The asteroid belt contains $\sim$ 200 asteroids larger than 100 km most of which are likely primordial bodies rather than collisional fragments. Very broadly this population can be grouped into two diverse but largely distinct groups: volatile-poor asteroids (mostly S-types), predominate in the inner belt while primitive asteroids (mostly C-types), predominate in the outer belt with C-types outnumbering S-types beyond 2.8 AU. These two populations have overlapping semimajor axis distributions.

These two populations have some broad physical differences which support an origin from two distinct populations. First, C-types, and the classes closely associated with them, show hydration bands or even water on their surface (Themis etc.), whereas the S-types do not [5]. If we consider C- and S-types as the parent bodies of the Carbonaceous and Ordinary chondrites respecitively then we find that there are strong distinctions in both Oxygen and Chromium isotope ratios [6, 7]. Combined, these data suggests that starting from two distinct parent populations, with diversity in each, is reasonable.

Thus 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 near Jupiter's starting location. Beyond the giant planets is the population of the "C-type" asteroids.

3. Scattering of small bodies

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 beyond the giant planets. We find that $\sim$0.5% of the "S-type" material is scattered back inward onto stable orbits in the asteroid belt. Of the initial C-type material from beyond Saturn, $\sim$0.5% reaches 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.

In conclusion, we are able to reproduce Mars' small mass as well as the orbital and taxonomic structure of the asteroid belt by taking into account the inward-then-outward gas-driven migration of Jupiter that is predicted by hydrodynamical simulations.

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