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

Kevin J. Walsh[1,2], Alessandro Morbidelli[2], Sean N. Raymond[3], David P. O'Brien[4] & Avi M. Mandell[5] , [1]Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302, USA, (kwalsh@boulder.swri.edu) [2]Université de Nice – Sophia Antipolis, CNRS, Observatoire de la Cô te d'Azur, B.P. 4229, 06304 Nice Cedex 4, France [3]Laboratoire d'Astrophysique de Bordeaux, 2 rue de l'Observatoire, 33270 Floirac, FRANCE [4]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, USA [5]NASA Goddard Space Flight Center, Code 693, Greenbelt, MD 20771, USA

Motivating Problem Dynamical simulations of terrestrial planet accretion consistently fail to produce reasonable Mars analogs; planets at Mars' orbital distance are systematically overestimated by an order of magnitude [1]. Recent results have found that the orbits and masses of the terrestrial planets can be matched if planetary embryos and planetesimals only existed in a narrow annulus stretching between 0.7–1.0 AU [2]. However, the truncation of the planetesimal disk at 1.0 AU is diff cult to explain. Here we explore the possibility that this truncation is due to the migration of the giant planets into the inner solar system. This migration must have occurred while the gas-disk was still present, during the f rst 3-10 Myr of solar system evolution. We focus on the survival of the asteroid belt as it provides a strong f rst-order constraint.

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 eventually Saturn is captured in the 2:3 mean motion resonance with Jupiter [3]. This conf guration 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 f nal mass and was captured in resonance.

This inward-then-outward migration scheme is robust, but the extents of the inward and outward migrations are unknown a priori due to the uncertainties in the disk properties and of the relative timescales of Jupiter and Saturn's growths. Thus, the distance from the Sun at which Jupiter's migration changed direction is essentially a free parameter in this scenario that we set by using the large-scale structure of the inner Solar System as a constraint.

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. 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.

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 of asteroids are not entirely separate from one another in semi-major axis but rather have overlapping distributions [4].

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 [5,6]. If we consider C- and S-types as the parent bodies of the Carbonaceous and Ordinary chondrites respecitively then we f nd that there are strong distinctions in both Oxygen and Chromium isotope ratios [7,8]. Combined, these data suggests that starting from two distinct parent populations, with diversity in each, is reasonable.

Thus we begin our simulations begin with two entirely separate parent populations of asteroids. First there is the planetesimal disk interior to Jupiter, from $\sim$0.7 AU out to Jupiter's starting location. The nominal simulation we present begins with Jupiter at 3.5 AU, and thus the inner planetesimal population, "S-types", extends to 3.0 AU. Between and beyond the giant and ice giant planets is the population of the "C-type" asteroids. We then investigate the f nal state of the asteroid belt region after an inward and outward migration of Jupiter.

Proposed scenario There is signif cant uncertainty concerning the growth and early dynamical evolution of the giant planets. We present a simplif ed scenario that is supported by an exploration of parameter space that embraces a large range of possibilities and demonstrates the robustness of the results. Throughout we maintain the fundamental assumption that Jupiter tacked at 1.5 AU.

The direction of migration is then reversed and the giant planets migrate outward together. On their way out, they capture Uranus and Neptune in resonance which then also migrate outwards. Saturn, Uranus and Neptune are fully grown by the end of the migration which occurs when Jupiter reaches 5.4 AU. The gas disk is dissipating exponentially, and the migration rate is therefore synched with the dissipation of the gas.

We begin with a fully-formed Jupiter starting at 3.5 AU, because the snow line marking the water condensation front is predicted to fall between 2.5 and 4.5 AU and is expected to be highly favorable for giant planet formation [9]. Saturn's 30 Earth mass ($M_\oplus$) core is initially at ∼4.5 AU and grows to 60 $M_\oplus$ in 10^5 years as Jupiter migrates inward. Rapid inward type-I migration of planetary cores has recently been found to be inhibited in more realistic models of disks, and therefore Saturn's core remains at 4.5 AU during this phase [10]. The cores of Uranus and Neptune are placed at ∼ 6 and 8 AU and grow from 5 $M_\oplus$, without migrating. When Saturn reaches 60 $M_\oplus$ it begins its inward migration [11] and rapid, runaway migration begins [12] and continues until Saturn enters the 2:3 resonance with Jupiter [3]. As required, Saturn reaches the 2:3 resonance when Jupiter is at 1.5 AU. The direction of migration is then reversed and the giant planets migrate outward together. On their way out, they capture Uranus and Neptune in resonance which then also migrate outwards. Saturn, Uranus and Neptune are fully grown by the end of the migration which occurs when Jupiter reaches 5.4 AU. The gas disk dissipates exponentially, and the giant planets' migration rate decreases accordingly.

The fina orbital configuratio of the giant planets is a compact chain of mean motion resonances that is consistent with their current orbital configuratio when their later dynamical evolution is considered [13].

Scattering of small bodies During Jupiter's inward migration it scatters about ∼15% of the planetesimals in the inner disk (the "S-types") onto orbits beyond 3 AU. Jupiter also shepherds nearly 1 Earth mass of material from 1-3 AU inward as it migrates, such that by the time of its migration reversal there is $\sim 2M_\oplus$ of material interior to 1 AU and a significan "scattered disk" of the S-type material exterior to Jupiter and Saturn.

When Jupiter and Saturn "tack" and begin their outward migration, they firs encounter this scattered disk of S-type material and only later begin encountering the "C-type" bodies that are initially located between and beyond the giant planets. We fin that ∼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 the Jupiter-Neptune region, about ∼0.5% is scattered into the asteroid belt, and ∼ 0.025% of the material initially beyond Neptune reaches the asteroid belt.

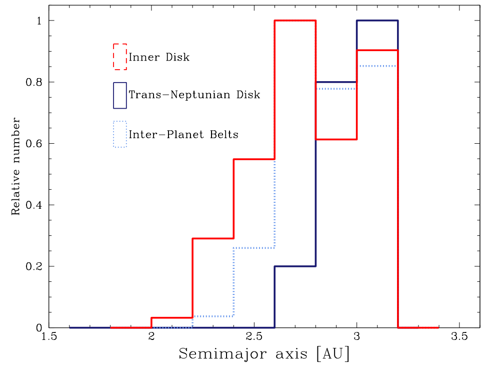

Figure 1: Distribution of fina semimajor axes for scattered planetesimals from the three main source regions.

The fina 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 limited in our calculations at 0.3, and are likely to be re-shuffle during the later instabilities that occur during the 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 after the later migration of the giant planets [14].

In conclusion, we are able to reproduce Mars' small mass as well as the S/C dichotomy 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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