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A record of planet migration in the main asteroid belt

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The main asteroid belt lies between the orbits of Mars and Jupiter, but the region is not uniformly filled with asteroids. There are gaps, known as the Kirkwood gaps, in distinct locations that are associated with orbital resonances with the giant planets[1]; asteroids placed in these locations will follow chaotic orbits and be removed[2]. Here we show that the observed distribution of main belt asteroids does not fill uniformly even those regions that are dynamically stable over the age of the Solar System. We find a pattern of excess depletion of asteroids, particularly just outward of the Kirkwood gaps associated with the 5:2, the 7:3 and the 2:1 Jovian resonances. These features are not accounted for by planetary perturbations in the current structure of the Solar System, but are consistent with dynamical ejection of asteroids by the sweeping of gravitational resonances during the migration of Jupiter and Saturn ∼4 Gyr ago.

The Kirkwood gaps have been explained by the perturbing effects of the giant planets that cause dynamical chaos and orbital instabilities on very long timescales in narrow zones in the main asteroid belt[2], but thus far it has not been established how much of the main belt asteroid distribution is accounted for by planetary perturbations alone. We compared the distribution of observed asteroids against a model asteroid belt uniformly populated in the dynamically stable zones. Our model asteroid belt was constructed as follows. Test particle asteroids were given eccentricity and inclination distributions similar to the observed main belt, but a uniform distribution in semimajor axis. We then performed a numerical integration for 4 Gyr of the test particles' orbital evolution under the gravitational perturbations of the planets using a parallelized implementation of a symplectic mapping[3,4]. Details of the simulation can be found in Supplementary Information.

We sorted the surviving particles into semimajor axis bins of width 0.03 AU. We compared the model asteroid belt with the observed asteroid belt, as shown in Fig. 1a. We find that the observed asteroid belt is overall more depleted than the model can account for, and there is a particular pattern in the excess depletion (Fig. 1a): there is enhanced depletion in the semimajor ranges spanning 2.81–3.11 AU and 3.34–3.47 AU; these regions are just exterior to the major Kirkwood gaps associated with the 5:2, 7:3 and 2:1 mean motion resonances (MMRs) with Jupiter; the semimajor axis ranges 2.72–2.81 AU and 3.11–3.23 AU, which are just interior to the 5:2 and the 2:1 resonances, do not show depletion. In addition the inner belt region, spanning 2.21–2.72 AU, shows significant excess depletion.

The above conclusions about the patterns of depletion are based on our model asteroid belt, which assumes uniform initial population of the dynamically stable zones. It is conceivable that the discrepancies between the model and the observations could be due to a non-uniform initial distribution of asteroids. However, the particular features we find cannot be explained by appealing to the primordial distribution of planetesimals in the solar nebula, nor to the effects of the mass depletion that occurred during the planet formation era (see Supplementary Information). As we show below, they can instead be readily accounted for by the effects of giant planet migration in the early history of the Solar System.

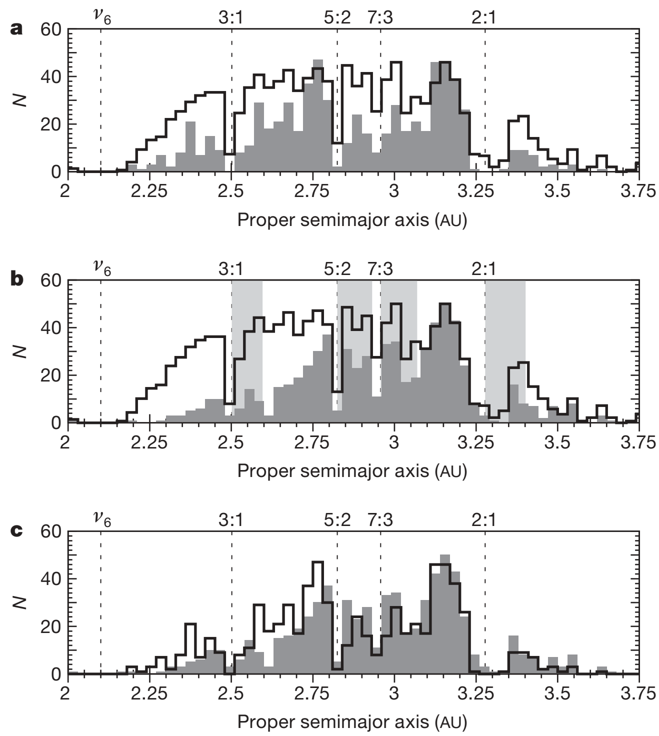

Figure 1 | Comparison of the observed main belt asteroid distribution with our simulated asteroid belt and results of the migration simulation. a, Solid line histogram, the distribution of asteroids remaining in our model asteroid belt at the end of the 4 Gyr simulation in which the asteroid belt region was initially uniformly populated with test particles and the planets were in their current orbits. Shaded histogram, our observational comparison sample, which consists of the 690 asteroids with absolute magnitude $H < 9.7$ (equivalent to diameters $D \gtrsim 50$ km, assuming a visual geometric albedo of 0.09), in the AstDys online data service[19] (details in Supplementary Information). The model asteroid belt (solid line) was normalized by multiplying all bins by a constant such that the value of the most-populous model bin equalled that of its corresponding bin in the observations. Vertical dashed lines, current positions of the ν_6 secular resonance and the strong Jovian MMRs associated with the major Kirkwood gaps. **b**, Solid line, initial distribution of test particles in the simulation with migrating planets. Shaded histogram, the distribution of test particles remaining at the end of the 100 Myr migration simulation. The post-migration test particle bins were normalized by multiplying all bins by a constant value such that the value of the most-populous bin equalled that of its corresponding bin in the initial conditions. The planet migration history followed the form of equation (1). Grey shading, regions swept by the strong Jovian MMRs. **c**, Comparison of the model asteroid belt subjected to planet migration and the observed asteroid belt. Solid line, distribution of observed large asteroids (the same as the shaded histogram in **a**). Shaded histogram, distribution of test particles remaining at the end of the 100 Myr migration simulation (the same as the shaded histogram in **b**).

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There is evidence in the outer Solar System that the giant planets—Jupiter, Saturn, Uranus and Neptune—did not form where we find them today. The orbit of Pluto and other Kuiper belt objects that are trapped in MMRs with Neptune can be explained by the outward migration of Neptune due to interactions with a more massive primordial planetesimal disk in the outer regions of the Solar System[5,6]. The exchange of angular momentum between planetesimals and the four giant planets caused the orbital migration of the giant planets until the outer planetesimal disk was depleted of most of its mass, leaving the giant planets in their present orbits[7–9]. As Jupiter and Saturn migrated, the locations of MMRs and secular resonances swept across the asteroid belt, exciting asteroids into terrestrial-planet-crossing orbits, thereby greatly depleting the asteroid belt population and perhaps also causing a late heavy bombardment in the inner Solar System[10–13].

We performed a computer simulation to test the hypothesis that the patterns of asteroid depletion inferred from Fig. 1a are consistent with planet migration. We used a total of 1,819 surviving test particles from the previous 4 Gyr simulation as initial conditions for a simulation with migrating planets. For the purposes of this simulation, we applied an external tangential force on each of the planets to simulate their orbital migration, so that a planet's semimajor axis evolved as follows[5]:

$$a(t) = a_0 + \Delta a[1 - \exp(-t/\tau)] \quad (1)$$

where a_0 is the initial semimajor axis, Δa is the migration distance, and τ is a migration rate e-folding time. Jupiter, Saturn, Uranus and Neptune had initial semimajor axes displaced from their current values by $\Delta a = +0.2$, -0.8, -3.0 and -7.0 AU, respectively; these values are consistent with other estimates of Jupiter's and Neptune's migration distances[6,7,9,14], but Uranus' and Saturn's migration distances are less certain. We used $\tau = 0.5$ Myr, which is near the lower limit inferred from Kuiper belt studies[15]. After 100 Myr of evolution under the influence of migrating planets, the 687 surviving test particles in the simulation were sorted and binned. The distribution of the survivors is shown in Fig. 1b.

We see directly that, in contrast with Fig. 1a, the asteroid belt distribution produced by the planet migration model matches qualitatively quite well the distribution of the observed asteroids (Fig. 1c). The patterns of excess depletion that we noted in Fig. 1a are explained well by the effects of the orbital migration of Jupiter and Saturn: the regions within the sweep zones of the 5:2, 7:3 and 2:1 Jovian MMRs show enhanced depletion, and the migration model also accounts for the excess depletion in the inner belt.

Of note is that the inner asteroid belt region (2.15–2.81 AU) is somewhat more depleted in the migration simulation than in the observations. The majority of depletion from this region found in our migration simulation is due to the sweeping ν_6 secular resonance. This powerful resonance removes asteroids from the main belt by secularly increasing their eccentricities to planet-crossing values[16]. The maximum eccentricity of an asteroid disturbed by the passage of the ν_6 resonance, and thereby the degree of asteroid depletion, is related to the sweeping speed: the slower the sweeping, the more the depletion[17]. The distances the planets migrate determine the ranges in asteroids' semimajor axes that are affected by the sweeping. In our simulation, as Jupiter and Saturn migrated, the ν_6 secular resonance swept inward across the entire main asteroid belt to its present location at ~ 2.1 AU, as shown in Fig. 2. But because the ν_6 resonance location is such a steep function of Saturn's semimajor axis (see Fig. 2), even modest proposed values of Saturn's migration distance result in all of the asteroid belt being affected by the passage of this resonance. Thus, the overall level of depletion of the asteroid belt is most strongly dependant on the speed of planet migration, and only secondarily on the migration distance. Because we used an exponentially decaying migration rate for the giant planets, the ν_6 resonance sweeping rate decreased as it approached its current location, thereby causing relatively greater asteroid depletion in the inner belt. Thus, the small but noticeable differences between the model and the observations in Fig. 1c are sensitive to the details of the time history of the planet migration speed.

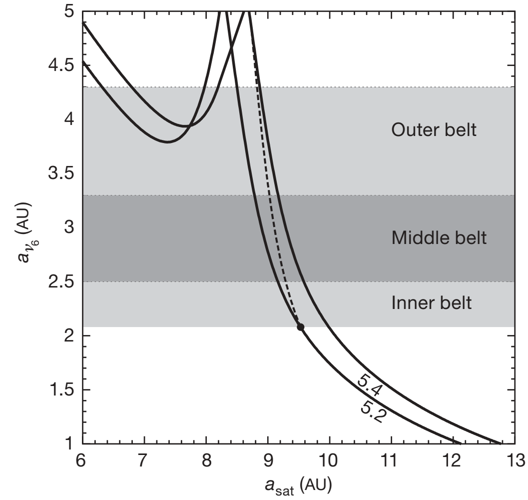

Figure 2 | The location of the ν_6 secular resonance as a function of Saturn's semimajor axis. This is calculated using linear secular theory, with a correction for the effects of the $(n+1)$:n MMRs, up to and including $n=8$, between Jupiter and Saturn[20]. A dot shows the current location of the ν_6. Labelled solid lines, calculations based on different fixed values of Jupiter's semimajor axis (given in AU). Dashed line, the path of the ν_6 resonance in our migration simulation in which Jupiter and Saturn migrated -0.2 and $+0.8$ AU, respectively.

We note that our model asteroid belt lost 62% of its initial pre-migration population, but the actual asteroid belt may have lost as much as ~90–95% of its asteroids by migration[18]. Because the overall level of asteroid depletion is particularly sensitive to the speed of planet migration, detailed exploration of the parameters of the planet migration model and comparison with observations of main belt asteroids may provide strong quantitative constraints on planet migration.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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