EVIDENCE FOR PLANET MIGRATION IN THE MAIN ASTEROID BELT: IMPLICATIONS FOR THE DURATION OF THE LATE HEAVY BOMBARDMENT D.A. Minton and R. Malhotra, Lunar and Planetary Laboratory, The University of Arizona, 1629 E. University Blvd. Tucson AZ 85721. daminton@lpl.arizona.edu

Introduction We show that the observed distribution of main belt asteroids does not uniformly fill the regions that are dynamically stable over the age of the solar system. The discrepancies indicate an overall trend of depletion that is highest near the inner edge of the asteroid belt and diminishes towards the location of the 2:1 mean motion resonance with Jupiter; in addition, there is excessive depletion of asteroids just outward of the well-known Kirkwood Gaps associated with jovian mean motion resonances. These features are not accounted for by planetary perturbations in the current dynamical structure of the solar system. We show that they are consistent with dynamical ejection of asteroids by the sweeping of mean motion resonances and of the ν_6 secular resonance during the migration of Jupiter and Saturn that has been proposed as the mechanism for initiating the Late Heavy Bombardment (LHB) ~ 4 Ga [1–3]. We will use the observed depletion of the asteroid belt as a constraint on the migration history of Jupiter and Saturn.

The observed craters on Mercury, Mars, and the Moon in the most heavily cratered regions have a common scaled projectile size frequency distribution that is well matched with the size frequency distribution of the main asteroid belt [2]. This implies that some size-independent (i.e. dynamical) depletion event occurred in the main asteroid belt well after the planetary crusts had solidified; its timing has been placed at ~ 3.9 Ga, corresponding to the period of Late Heavy Bombardment (LHB) inferred from lunar geochronology [e.g., 4, 5].

Numerical experiment Is there evidence of the mass depletion event associated with the LHB preserved in the distribution of asteroids in the main belt? In order to answer this question we performed a simple numerical experiment. We compared the distribution of observed asteroids with absolute magnitude $H < 9.7$ (which corresponds to diameters $D \gtrsim 50$ km assuming a visual geometric albedo of 0.09) against a model asteroid belt which is uniformly populated in the dynamically stable zones.

Our model asteroid belt was constructed as follows. The test particle asteroids were given an eccentricity and inclination distribution similar to the observed main belt, but a uniform distribution in semimajor axis. We then did a numerical integration of their orbital evolution under the gravitational influence of the planets, using the public-domain N-body integrator MERCURY [6]. In our simulation, the planets interacted with each other and perturbed the test particles, but the test particles had no effect on the planets. The test particles were considered lost if they passed within 3 Hill radii of a planet or collided with the Sun.

The simulation was ended after 100 My of evolution, and the surviving particles were binned into 0.05 AU proper semimajor axis bins. The proper semimajor axis of a particle was calculated by taking the mean of its semimajor axis for its first 1 My of orbital history. We found that the particle loss history for each bin has two phases, an initial phase when the most unstable particles in the bin are lost, typically lasting 0.1–1 My, and a second phase when the loss rate is relatively slow and is characterized well as linear in $\log t$. A linear regression in $\log t$ was performed on the second phase of the loss history data for each semimajor axis bin, and the number of particles remaining in each bin after 4 Gy was estimated by extrapolation. The estimated number of test particles in each bin was compared with the proper semimajor axis distribution of observed $H < 9.7$ asteroids obtained from the AstDys online information service [7].

Result and discussion The discrepancy between the model asteroid belt and the observed asteroid belt is shown in Fig. 1, where the percent discrepancy is defined as

$$\text{Percent discrepancy} = \frac{N_{sim} - N_{obs}}{N_{sim}} \times 100, \quad (1)$$

where N_{sim} and N_{obs} are the number of asteroids per bin in the simulation and in the observed main belt population, respectively. Overall, we find that the discrepancy is highest at the inner edge of the main belt and decreases to near-zero at the location of the 2:1 jovian mean motion resonance; in addition, there is enhanced discrepancy just exterior to the major Kirkwood gaps.

Any mechanism invoked to explain the discrepancy must account for the features seen in Fig. 1, namely that the discrepancy tends to decrease as a function of semimajor axis from the inner edge of the asteroid belt to the location of the 2:1 mean motion resonance with Jupiter, with enhanced depletion in regions outward of the major Kirkwood gaps.

The observed discrepancy is most consistent with the sweeping of both mean motion and secular resonances during a late migration of Jupiter and Saturn that has been implicated as the mechanism responsible for the LHB [1–3]. As Jupiter and Saturn migrated, the locations of mean motion and secular resonances swept across the asteroid belt, exciting asteroids into terrestrial planet-crossing orbits [3, 8].

The ν_6 resonance, in particular, may have swept inward through the entire asteroid belt region as Saturn migrated outward from about 8 AU to its present location. The ν_6 resonance removes asteroids from the main asteroid belt by increasing their eccentricity above planet-crossing values so that they either collide with a planet or are perturbed into a new orbit. The efficiency of removal is related to the rate of sweeping: the faster Saturn migrated, the fewer asteroids were removed. The overall trend of depletion in the asteroid belt found in Fig. 1 is consistent with an outward migration of Saturn at a rate that decreased with time.

The size of the regions of enhanced depletion just outward of the Kirkwood gaps associated with the 3:1, 5:2, 7:3, and 2:1 jovian mean motions resonances are explained by an inward migration of Jupiter by ~ 0.2–0.4 AU. This distance is consistent with other estimates of Jupiter's migration distance [9–12]. These regions are highlighted in Fig. 1.

This evidence, together with the evidence that the cratering records of the terrestrial planets associated with the LHB appear to have been dominated by impactors originating in the main asteroid belt [2], lends support to the hypothesis that a late migration of the outer giant planets was responsible for producing the LHB.

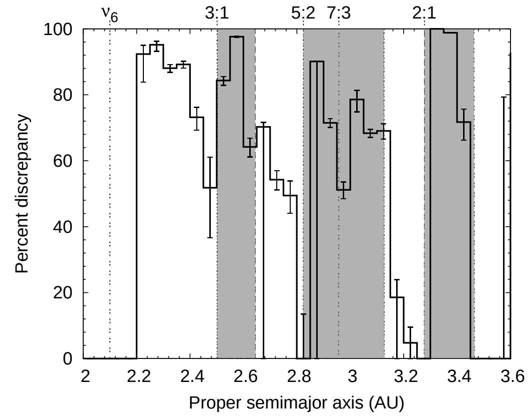

Figure 1: The discrepancy between the observed population of asteroids with $H < 9.7$ and a model asteroid belt. The current positions of the ν_6 secular resonance and the strong jovian mean motion resonances associated with the major Kirkwood gaps are shown. The observed discrepancy may be explained as depletion by orbital sweeping resonances during the migration of Jupiter and Saturn. The shaded regions are the regions where strong jovian mean motion resonances would have swept if Jupiter's initial semimajor axis had been 5.5 AU.

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