

SECULAR RESONANCE SWEEPING OF ASTEROIDS DURING THE LATE HEAVY BOMBARDMENT. D.A. Minton, R. Malhotra, Lunar and Planetary Laboratory, The University of Arizona, 1629 E. University Blvd. Tucson AZ 85721. daminton@lpl.arizona.edu.

Introduction: The Late Heavy Bombardment (LHB) was a period of intense meteoroid bombardment of the inner solar system that ended approximately 3.8 Ga [e.g., 1–3]. The likely source of the LHB meteoroids was the main asteroid belt [4]. It has been suggested that the LHB was initiated by the migration of Jupiter and Saturn, causing Main Belt Asteroids (MBAs) to become dynamically unstable [5, 6]. An important dynamical mechanism for ejecting asteroids from the main asteroid belt into terrestrial planet-crossing orbits is the sweeping of the ν_6 secular resonance. Using an analytical model of the sweeping ν_6 resonance and knowledge of the present day structure of the planets and of the main asteroid belt, we can place constraints on the rate of migration of Saturn, and hence a constraint on the duration of the LHB.

The semimajor axis location of the ν_6 resonance depends on the semimajor axes of both Jupiter and Saturn, though it is more strongly dependent on Saturn's location than Jupiter's. Also, the planetary migration that is thought to have occurred in the early solar system due to the scattering of icy planetesimals likely resulted in Jupiter having migrated inward by only ~ 0.2 AU, but Saturn may have migrated outward a much greater distance [7]. In the current solar system, the location of the ν_6 resonance is at ~ 2.1 AU and defines the inner edge of the main asteroid belt. If the pre-LHB semimajor axes of Jupiter and Saturn were $+0.2$ AU and -1.8 AU from their current location, then the ν_6 would have swept the asteroid belt from about 3.3 AU to its present location. This is somewhat simplified because the effects of mean motion resonances, including both Jupiter-asteroid resonances and the Jupiter-Saturn 2:1 resonance, as well as the secular effects of the more massive primordial asteroid belt will complicate the dynamics. We will ignore these complications for now and consider a simplified system that is only affected by a sweeping ν_6 resonance.

Consider a main belt asteroid perturbed by the ν_6 secular resonance. When the planet inducing the secular perturbation – Saturn in this case – migrates, this is equivalent to a time-variable frequency, g_p , of the secular forcing function for the asteroid. In the linear approximation, the time-varying secular forcing frequency is given by:

$$g_p = g_{p,0} + \lambda t. \quad (1)$$

Following Ward et al. (1976) [8], we can define the moment of exact resonance crossing as $t = 0$, therefore $g_{p,0} = g_0$. The resonance Hamiltonian describing the secular perturbations of the asteroid's orbit is given by

$$H_{res} = -2\lambda t J - \varepsilon \sqrt{2J} \cos \phi, \quad (2)$$

where $\phi = \varpi_p - \varpi$ is the resonance angle that measures the asteroid's longitude of perihelion relative to Saturn's, and J is the canonically conjugate generalized momentum which is related to the asteroid's orbital semimajor axis a and eccentricity e , $J = \sqrt{a}(1 - \sqrt{1 - e^2})$. (Since a is unchanged by

the secular resonance perturbation, the dynamical changes in J due to the secular perturbation reflect changes in the asteroid's eccentricity e .) Using Poincaré variables, $(x, y) = \sqrt{2J}(\cos \phi, -\sin \phi)$, the equations of motion derived from this Hamiltonian are:

$$\dot{x} = -2\lambda ty, \quad (3)$$

$$\dot{y} = 2\lambda tx + \varepsilon. \quad (4)$$

These equations can be solved analytically to obtain the change in the value of $J = \frac{1}{2}(x^2 + y^2)$ from its initial value, J_i at time $t_i \rightarrow -\infty$, to its final value J_f at $t \rightarrow \infty$, as the asteroid is swept over by the secular resonance:

$$J_f = \frac{\pi\varepsilon^2 + 2J_i|\lambda| + \varepsilon\sqrt{8\pi J_i|\lambda|} \cos \beta}{2|\lambda|}, \quad (5)$$

where β is an arbitrary phase that depends on the asteroid's initial phase ϖ_i . Considering all possible values of $\cos \beta \in -1, +1$, an asteroid that encounters a sweeping secular resonance will have a final eccentricity bounded by:

$$e_{\pm} = \sqrt{1 - \left[1 - \frac{\pi\varepsilon^2 + 2J_i|\lambda| \pm \varepsilon\sqrt{8\pi J_i|\lambda|}}{2|\lambda|\sqrt{a}}\right]^2}. \quad (6)$$

A comparison between this analytical estimate and the numerically integrated equations of motion for an ensemble of asteroids is shown in Fig. 1.

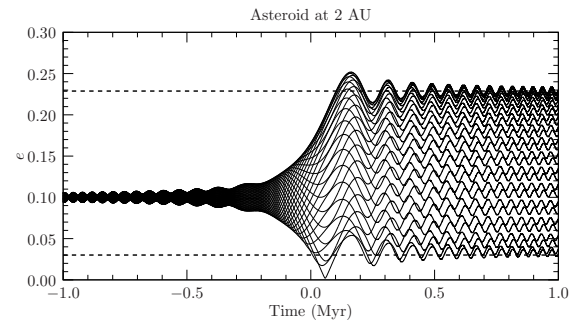


Figure 1: The integrated equations of motion given by Eqns. (3) and (4) for a family of massless particle at 2 AU with $e_i = 0.1$ and uniformly distributed initial phases $0 < \varpi_i < 2\pi$. Current solar system values of the eccentricity of Jupiter and Saturn were used. The rate λ was chosen to approximate the outward migration of Saturn at a rate of 1 AU/Myr, with Saturn ending at its current location. The dashed lines represent the envelope of the predicted final eccentricity using Eqn. (6).

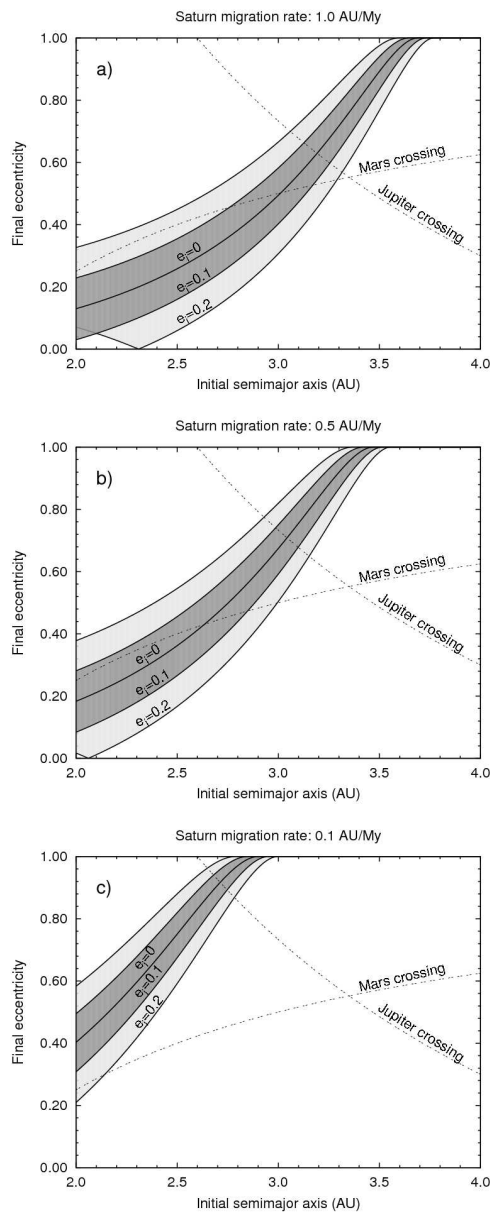


Figure 2: Estimated final eccentricity of an asteroid as a function of the initial asteroid semimajor axis and eccentricity for three different migration rates of Saturn using Eqn. (6). Asteroids with a finite initial eccentricity can have a range of final eccentricities, depending on their initial apsidal phase, ϖ_i , which is shown by shaded regions of the eccentricity curve. An unphysical branch of Eqn. (6) has been omitted from these plots.

It is thought that the pre-LHB MBAs were already dynamically excited due to processes occurring at the time of planet formation and solar nebula dispersal. [9]. Fig. (1) illustrates the fact that secular resonance sweeping can both excite and damp eccentricities of asteroids that have a finite initial eccentricity. Using current solar system values for the coefficient ε , an estimated final eccentricity as a function of initial asteroid semimajor axis, initial asteroid eccentricity, and Saturn's migration is shown in Fig. 2. Note that slower sweep rates yield higher eccentricity excitation. The eccentricity needed to reach both Mars and Jupiter-crossing orbits as a function of semimajor axis is also shown.

If we adopt the criterion that in order to enter the LHB impactor population, MBAs in the 2–3 AU zone must achieve at least a Mars-crossing orbit, then it follows from our results above that Saturn's migration distance must be ~ 1 AU and its maximum migration rate must be between ~ 0.1 – 1.0 AU/Myr, or, equivalently, a migration duration exceeding ~ 10 Myr. These results also depend strongly on the eccentricity of Saturn during the migration. The coefficient ε is proportional to the eccentricity of Saturn. Therefore if Saturn's orbit were more circular during the LHB than it is today, then the migration time would need to be correspondingly longer to produce the same amount of eccentricity excitation.

References:

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