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Constraining Saturn's Final Migration with GPU Acceleration

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Abstract

The extreme low density of material and degree of orbital excitation in the modern asteroid belt starkly contrasts that of the planetary regimes, and implies a unique evolutionary history [1]. Because many objects in the belt are thought to represent the unprocessed building blocks of planet formation, understanding its dynamical history is supremely important. While modern terrestrial accretion models broadly reproduce the belt's primordial depletion [2] and orbital excitation (for example; [3]), all previous studies fail to reproduce the inner (a <2.5 au) belt's inclination structure (eg; [4, 3, 2]). We use a modernized computational algorithm (GPU (graphics processing unit) accelerated; [5]) to accurately model the final phase of Saturn's orbital migration. We find that the inclination problem is consistently resolved when the precise dynamics of the Jupiter-Saturn system's approach to its modern configuration is accounted for.

1. Introduction

The giant planet instability (the so-called Nice Mode; [6]) excites orbits in the asteroid belt via eccentric forcing (eg: secular perturbations). Furthermore, the violent sweeping of strong secular resonances across the belt should account for either some [3] or all [2] of the mass discrepancy between the modern and primordial belt (some ∼4 orders of magnitude; [7]). However, simulations of the event [4, 3, 2] consistently fail to reproduce the ratio of asteroids with inclinations above to those below the ν_6 secular resonance in the inner belt (∼0.08 in the modern solar system). Specifically, the sweeping of the ν_6 and ν_{16} resonances during the giant planet instability excite and strand asteroids on stable, high inclination orbits that are not observed in the modern belt. In fact, most previous studies report ratios of asteroids about ν_6 that are greater than unity.

2. Dynamical Mechanism

We argue that the absence of asteroids (figure 1) with orbits that precess between 24-28 "/yr (arc-seconds per year) is related to the inclination distribution problem; and a remnant of the final phase of Saturn's orbital migration. Encounters with leftover planetesimals cause Saturn's orbit to diverge from Jupiter's. Through this process, the two planets' mutual interactions weaken, and Saturn's orbital precession slows. In the modern solar system, Saturn's precession is related to the g_6 eigenfrequency of 28.22 "/yr that, in turn, drive the ν_6 resonance. However, because of the Jupiter-Saturn system's modern proximity to the 5:2 mean motion resonance, the g_6 rate must have dipped below the modern value before eventually rising back up (figure 2). This is a result of secular effects amplifying near mean motion resonance (see discussion in [8]).

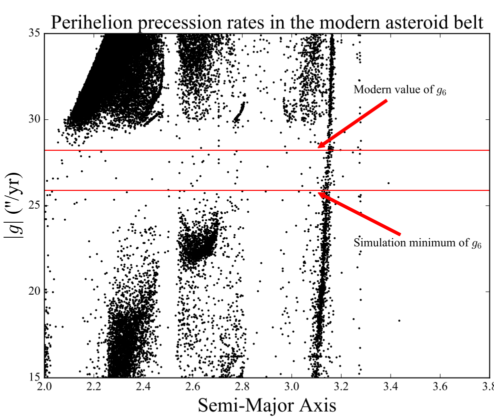

Figure 1: Orbital precession rates in the modern asteroid belt.

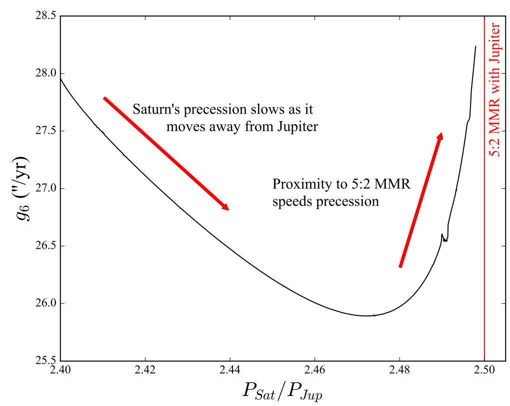

Figure 2: The solar system's g_6 eigenfrequency as a function of the Jupiter-Saturn period ratio.

3. Summary and Conclusions

We present numerical simulations to show that this cycling of the g_6 rate dramatically alters the asteroid belt's inclination structure. Our initial populations of asteroids are drawn from the results of terrestrial accretion models [2]. The sweeping of ν_6 in our simulations excites the eccentricities of moderate inclination ($\sim$10< i <25°) asteroids and places them on planet-crossing orbits. These asteroids are then removed, yielding final asteroid belts in good agreement with the real one. The median ratio of asteroids above to below ν_6 in our systems is $\sim$0.5, with some system possessing ratios near zero. Thus, our work offers a self-consistent explanation for the inner asteroid belt's inclination distribution.

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