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The primordial excitation and clearing of the asteroid belt—Revisited

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Dedicated to the memory of G. Wetherill, who first proposed that planetary embryos formed in the primordial asteroid belt and were responsible for its mass depletion and orbital sculpting

Abstract

We have performed new simulations of two different scenarios for the excitation and depletion of the primordial asteroid belt, assuming Jupiter and Saturn on initially circular orbits as predicted by the Nice Model of the evolution of the outer Solar System [Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., 2005. Nature 435, 466–469; Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F., 2005. Nature 435, 459–461; Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R., 2005. Nature 435, 462–465]. First, we study the effects of sweeping secular resonances driven by the depletion of the solar nebula. We find that these sweeping secular resonances are incapable of giving sufficient dynamical excitation to the asteroids for nebula depletion timescales consistent with estimates for solar-type stars, and in addition cannot cause significant mass depletion in the asteroid belt or produce the observed radial mixing of different asteroid taxonomic types. Second, we study the effects of planetary embryos embedded in the primordial asteroid belt. These embedded planetary embryos, combined with the action of jovian and saturnian resonances, can lead to dynamical excitation and radial mixing comparable to the current asteroid belt. The mass depletion driven by embedded planetary embryos alone, even in the case of an eccentric Jupiter and Saturn, is roughly 10–20× less than necessary to explain the current mass of the main belt, and thus a secondary depletion event, such as that which occurs naturally in the Nice Model, is required. We discuss the implications of our new simulations for the dynamical and collisional evolution of the main belt.

Keywords: Asteroids, dynamics; Resonances; Origin, Solar System

1. Introduction

It has long been recognized that the primordial asteroid belt must have contained hundreds or thousands of times more mass than the current asteroid belt [e.g., Lecar and Franklin (1973), Safronov (1979), Weidenschilling (1977), Wetherill (1989) and many others]. Reconstructing the initial mass distribution of the Solar System from the current masses of the planets and asteroids, for example, yields a pronounced mass deficiency in the asteroid belt region relative to an otherwise smooth distribution for the rest of the Solar System (Weidenschilling, 1977). To accrete the asteroids on the timescales inferred from meteoritic evidence would require hundreds of times more mass than currently exists in the main belt (Wetherill, 1989).

In addition to its pronounced mass depletion, the asteroid belt is also strongly dynamically excited. The mean proper eccentricity and inclination of asteroids larger than ∼50 km in diameter are 0.135 and 10.9°, respectively (from the catalog of Knežević and Milani, 2003), which is significantly larger than can be explained by gravitational perturbations amongst the asteroids or by simple gravitational perturbations from the planets (Duncan, 1994). The fact that the different taxonomic types of asteroids (S-type, C-type, etc.) are radially mixed somewhat throughout the main belt, rather than confined to delineated zones, indicates that there has been significant scattering in semimajor axis as well (Gradie and Tedesco, 1982). A number

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of models have been developed in order to explain these characteristics of the asteroid belt. The two most promising models both involve the influence of the outer planets, primarily Jupiter and Saturn.

In the first scenario, the depletion of the solar nebula causes secular resonances with Jupiter and Saturn to sweep through the asteroid belt, exciting the eccentricities and inclinations of asteroids and, possibly coupled with gas drag, dynamically eliminating asteroids from the main belt on a timescale of $\sim$1 Myr (Heppenheimer, 1980; Ward, 1981; Lemaitre and Dubru, 1991; Lecar and Franklin, 1997; Nagasawa et al., 2000). In the second, lunar- to Mars-mass planetary embryos that form in the asteroid belt, combined with jovian and saturnian resonances, drive the excitation and clearing of the asteroid belt on a timescale of 10–100 Myr (Wetherill, 1992; Chambers and Wetherill, 1998, 2001; Petit et al., 2001).

Nearly all of the work done on both of these subjects assumes that, at the time, the outer planets were on orbits similar to their current ones [a few, e.g., Chambers and Wetherill (2001) and Petit et al. (2001), test larger eccentricities]. However, over the past few decades it has become increasingly clear that the outer planets formed on orbits that may have been substantially different from those they follow in the present Solar System. Work starting with Fernandez and Ip (1984) and Malhotra (1993, 1995) has shown that Saturn, Uranus, and Neptune would have migrated outwards and Jupiter would have migrated slightly inwards due to gravitational interactions with a residual disk of planetesimals left over from planet formation.

As described further in Section 3, the most recent model (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005) strongly suggests that the initial system of outer planets was very compact (all within $\sim$15 AU of the Sun), with nearly circular and co-planar orbits. Slow migration of the planets would be driven by interactions with the planetesimal disk, but rapid migration and the excitation of the giant planets' orbital eccentricities to their current values did not occur until Jupiter and Saturn crossed their mutual 2:1 mean–motion resonance $\sim$600 Myr after the Solar System formed. That model will be referred to here as the Nice Model, as all of the authors were working at the Observatoire de Nice when it was developed.

In this paper we revisit the excitation and depletion of the asteroid belt by sweeping secular resonances and embedded planetary embryos in the context of the Nice Model, in particular taking into account that the primordial orbits of Jupiter and Saturn were almost circular and co-planar. In Section 2 we review the work to date on the various means of dynamically exciting and depleting the asteroid belt. In Section 3 we describe in more detail the Nice Model and its implications for the primordial evolution of the asteroid belt. In Sections 4 and 5 we describe our new modeling of sweeping secular resonances in the asteroid belt and the excitation of the asteroid belt by embedded planetary embryos and compare our results to previous work. Finally, in Section 6 we compare our simulations of both processes and discuss the implications of our new modeling for the evolution of the asteroid belt.

2. Mechanisms for asteroid belt excitation and depletion

Originally, a collisional origin was suggested for the mass depletion in the asteroid belt (Chapman and Davis, 1975). The difficulty of collisionally disrupting the largest asteroids, coupled with the survival of Vesta's basaltic crust, however, suggests that collisional grinding was not the cause of the mass depletion (Davis et al., 1979, 1985, 1989, 1994; Wetherill, 1989; Durda and Dermott, 1997; Durda et al., 1998; Bottke et al., 2005a, 2005b; O'Brien and Greenberg, 2005). A dynamical event must have occurred that cleared out most of the original mass of the asteroid belt, and in addition drove it to its current dynamically-excited and radially-mixed state. As reviewed by Petit et al. (2002) and discussed in more detail in the following sections, the two most promising dynamical mechanisms are the sweeping of secular resonances through the asteroid belt as the solar nebula was being depleted and the excitation of the asteroid belt by embedded planetary embryos.

2.1. Sweeping secular resonances

Secular resonances occur when the precession rate of a body's longitude of perihelion $\dot{\varpi}$ or of its longitude of ascending node $\dot{\Omega}$ is equal to one of the eigenfrequencies of the Solar System. For the asteroid belt and terrestrial planet region, the most important secular resonances, symbolized as ν_i, correspond to the eigenfrequencies dominated by Jupiter and Saturn. ν_5 and ν_6 occur when $\dot{\varpi}$ for a given body matches the eigenfrequencies g_5 and g_6, which are dominated by $\dot{\varpi}$ of Jupiter and Saturn, respectively. These resonances cause eccentricity changes. ν_{15} and ν_{16} occur when $\dot{\Omega}$ for a given body matches the eigenfrequencies f_5 and f_6, which are dominated by $\dot{\Omega}$ of Jupiter and Saturn, respectively. These resonances lead to inclination changes. The precession rates of bodies in the Solar System, and hence the positions of secular resonances, are determined by the gravitational potential of the planetary system.

Heppenheimer (1980) and Ward (1981) first suggested that as the solar nebula was being depleted early in the Solar System's history, the changing gravitational potential due to that event would cause the locations of secular resonances to change, hence 'sweeping' through the asteroid belt and the rest of the Solar System. Subsequent work, e.g., Lemaitre and Dubru (1991) and Lecar and Franklin (1997), explored this idea in more detail, with the latter including the effects of gas drag as well. Lecar and Franklin (1997) found that the boosting of orbital eccentricities by secular resonance sweeping, coupled with the fact that gas drag causes a rapid decay of eccentric orbits towards the Sun, could at least partly explain the orbital eccentricities and mass depletion of the asteroid belt, as well as the radial mixing of asteroid taxonomic types. The inclinations of asteroids, however, could not be reproduced.

All of these works assumed a uniformly decaying nebula, which keeps the same profile as its density decreases. Nagasawa et al. (2000, 2001, 2002) have extended that work to study non-uniform nebula clearing, such as the nebula clearing radially from the inside outwards, or where the nebula is cleared by a gap that expands outwards from Jupiter's orbit. Nagasawa et al. (2000) found that of all scenarios, the inside-out clearing of the solar nebula would do the best job of reproducing the eccentricities and inclinations of the asteroid belt (albeit for the unlikely case where the nebula is on the ecliptic plane rather than the invariant plane of Jupiter and Saturn, where the latter is defined as the plane orthogonal to the angular momentum vector of the Jupiter–Saturn system). They found that the e and i distribution of the asteroid belt could be reproduced if the inner edge of the solar nebula moved from 5 to 10 AU on a timescale greater than 3×10^5 yr. This is consistent with observational constraints on the timescale of nebula depletion around young solar-type stars (e.g., Strom et al., 1993; Zuckerman et al., 1995; Kenyon and Hartmann, 1995), which suggest that the nebula depletion timescale is 1–10 Myr with an average of ~3 Myr.

In the inside-out depletion model, e and i would be excited in the asteroid belt after the nebula had been removed from that region. Thus, radial migration caused by gas drag could not occur. Consequently, the removal of asteroids from the belt found in the uniform nebula clearing case (Lecar and Franklin, 1997) would not occur, and the overall mass depletion of the belt would not be nearly as pronounced as in the uniform nebula clearing case or in the case where the asteroid belt is excited and depleted by embedded planetary embryos (described in Section 2.2). Finally, further work (Nagasawa et al. 2001, 2002) showed that in the more realistic case where the nebula plane coincides with the invariant plane of Jupiter and Saturn, the excitation of inclination is greatly diminished.

While it can be argued that the excitation and depletion of the current asteroid belt is better reproduced by the embedded planetary embryo model than by sweeping secular resonances (e.g., Petit et al., 2002), it is important to address the issue of secular resonance sweeping here. Since we are also re-evaluating the effects of planetary embryos embedded in the asteroid belt in the context of the Nice Model, it is necessary to reconsider the sweeping secular resonance model under the same conditions in order to accurately and self-consistently compare the two processes.

2.2. *Embedded planetary embryos*

Safronov (1979) first suggested that Mars- to Earth-mass planetary embryos left over from the accretion process could lead to the excitation and depletion of the asteroid belt. In his scenario, these embryos would be scattered by Jupiter and pass through the asteroid belt. Petit et al. (1999) modeled that scenario in detail and showed that it cannot fully explain the observed mass depletion and dynamical excitation of the asteroid belt, especially in terms of inclination.

A much more promising scenario is to have the planetary embryos reside in the asteroid belt, as first suggested by Wetherill (1992). That model, and subsequent direct N-body integrations of planetary embryos in the asteroid belt and terrestrial planet region (e.g., Chambers and Wetherill, 1998, 2001), showed that the planetary embryos would be perturbed by one another and by jovian and saturnian resonances, becoming excited and often being driven out of the asteroid belt. Generally it is assumed that Jupiter and Saturn were on their current orbits when this process started. In 2/3 of the simulations of Chambers and Wetherill (1998, 2001), the asteroid belt is entirely cleared of embryos within tens to hundreds of Myr. In the remaining ~1/3 of the simulations an embryo remained on a stable orbit in the asteroid belt.

Petit et al. (2001) modeled the effects of such planetary embryos on a population of massless asteroids. They found that, for essentially any initial distributions of planetary embryos in the main-belt region, most asteroids would be dynamically eliminated from the asteroid belt with a median lifetime of only a few Myr and the remaining asteroids would have orbital a, e, and i distributions roughly similar to the current distribution. In addition, the radial mixing of different asteroid taxonomic types was reproduced in their simulations. The embedded planetary embryo model, then, is capable of reproducing reasonably well the current characteristics of the asteroid belt, at least under the assumption that Jupiter and Saturn were initially on their current orbits. Here we address the same scenario in the context of the Nice Model.

3. The Nice model and its implications for the early asteroid belt evolution

Work starting with Fernandez and Ip (1984) and Malhotra (1993, 1995) demonstrated that a residual disk of planetesimals left over from planet formation could drive the migration of the outer planets. This scenario has been subsequently explored in more detail by a number of researchers, aided in a large part by vast increases in computer speed (e.g., Hahn and Malhotra, 1999; Gomes et al., 2004).

The most recent work on this subject (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005), referred to here at the Nice Model, suggests the following scenario: (1) the initial system of outer planets was very compact (all within 15 AU of the Sun) and their orbits were nearly circular and coplanar; (2) the planets slowly migrated for hundreds of Myr due to gravitational interactions with a disk of planetesimals stretching from outside Neptune's orbit at ~15 AU to about 30–35 AU; (3) after ~600 Myr of slow migration, Jupiter and Saturn crossed their mutual 2:1 mean-motion resonance (MMR), triggering the Late Heavy Bombardment (LHB), capturing the current Trojan asteroid populations, and rapidly driving the outer planets to their current, moderately excited, orbital configuration.

In this work, we re-evaluate the scenarios described in Sections 2.1 and 2.2 for the primordial excitation and clearing of the asteroid belt in the context of the Nice Model. We adopt the initial orbits of Jupiter and Saturn that were found by Gomes et al. (2005) to best reproduce both the current orbits of the outer planets and the timing of the LHB: $a_j = 5.45$, $a_s = 8.18$, $e_j = e_s = 0$, $i_j = 0$, and $i_s = 0.5°$. The major qualitative differences between this configuration and the current configuration of Jupiter and Saturn is that in the Nice Model, they have much lower eccentricity and inclination than their current orbits, Jupiter is slightly further out from the Sun, and Saturn is closer to the Sun. The migration of Jupiter and Saturn is not included in our simulations because the scenarios for the excitation and depletion of the asteroid belt described in Sections 2.1 and 2.2 would be completed well before the LHB occurs, and the migration of Jupiter and Saturn before the LHB in the Nice Model is slow compared to their migration in the time immediately following the LHB.

Having the outer planets on nearly circular orbits with somewhat different a than their current values would substantially change the character of both the sweeping secular resonance model (Section 2.1) and the embedded planetary embryo model (Section 2.2) for the excitation and clearing of the primordial asteroid belt. In the case of the secular resonance sweeping model, the strengths of the ν_5, ν_6, ν_{15}, and ν_{16} secular resonances are a function of the eccentricities and inclinations of Jupiter and Saturn (Morbidelli and Henrard, 1991). In addition, the locations of these secular resonances (i.e., their positions after the nebula has been fully depleted) will be shifted relative to their current positions. Hence, when compared to the simulations of Nagasawa et al. (2000) and other authors, it is expected that the semimajor-axis range over which the asteroids' e and i will be excited may change somewhat and the degree of excitation of their e and i will be lower.

In the case of the embedded planetary embryo model, Chambers and Wetherill (2001), Chambers and Cassen (2002) and Petit et al. (2001) found that the orbits of Jupiter and Saturn are important in determining the efficiency and speed at which embryos and asteroids are cleared from the asteroid belt. Those researchers found that starting Jupiter and Saturn on orbits with twice their current eccentricities increased the rate of exciting and clearing bodies from the asteroid belt region (the case of a circular Jupiter and Saturn was not treated). This is partly because larger planetary eccentricities excite larger eccentricities amongst the embryos, which in turn excite the asteroids, but primarily because the strengths of both secular and mean-motion resonances with Jupiter and Saturn are a function of the eccentricities of the planetary orbits (Morbidelli and Henrard, 1991; Moons and Morbidelli, 1993).

Thus, the situation should be substantially different if Jupiter and Saturn were on the quasi-circular orbits predicted by the Nice Model while planetary embryos were present in the asteroid belt. A reasonable qualitative estimate is that the excitation and depletion of the asteroid belt would be less rapid than found in the Petit et al. (2001) simulations. This would have profound implications for the degree of collisional evolution that may have occurred in the main belt during its massive, primordial phase while it was being excited and depleted.

In the context of the Nice Model, it is important to realize that, in addition to the processes outlined in Section 2, the crossing of the 2:1 resonance by Jupiter and Saturn also had important effects on the asteroid belt. Gomes et al. (2005) found that when Jupiter and Saturn cross their mutual 2:1 MMR, their eccentricities and inclinations are boosted and they migrate to their present orbital configuration on a timescale of a few tens of Myr, causing a second episode of powerful secular resonance sweeping through the asteroid belt region. This effect is different and separate from the first secular resonance sweeping that occurs during the depletion of the solar nebula. The secondary sweeping of secular resonances through the asteroid belt is largely responsible for the LHB.

In a putative case where all of the asteroids in the belt have orbits with $e \sim i \sim 0$ at the time of the 2:1 resonance crossing, the sweeping secular resonances driven by the subsequent planetary migration can only increase the asteroids' e and i, so that essentially all bodies are driven out of the belt (Levison et al., 2001). Conversely, in the case where the asteroid belt is already dynamically excited, the sweeping secular resonances can decrease the eccentricities and inclinations of some asteroids on excited orbits, thus leaving those objects in the belt. For instance, assuming that the eccentricity and inclination distribution in the main belt at the time of the 2:1 resonance crossing was equivalent to the current distribution, Gomes et al. (2005) showed that, for the planetary migration rates following the 2:1 resonance crossing in the Nice model, statistically $\sim$5 to 10% of the asteroids survive in the main belt. Hence, for there to be an asteroid belt today, it must have already been dynamically excited at the time of the 2:1 resonance crossing. The primordial dynamical excitation mechanism need not exactly reproduce the current orbital distribution of asteroids, as the secular resonance sweeping following the 2:1 crossing will reshuffle the orbital distribution of the surviving asteroids, but it must be able to yield e and i comparable to the current values in the asteroid belt.

Since the secular resonance sweeping driven by planet migration only affects e and i, but not a, the primordial dynamical excitation mechanism must still be able to explain the radial mixing of different asteroid taxonomic types. Collisional processes subsequent to the orbital excitation (Charnoz et al., 2001) may give some radial mixing—however, this may not be very effective for large asteroids, whereas the radial mixing is apparent at all sizes. Similarly, it must still be able to explain part of the mass depletion of the asteroid belt, but the depletion need not be as severe as in the classical models—the mass remaining in the asteroid belt by the time of the LHB needs only to be reduced to $\sim$10–20$\times$ the current mass, as the secular resonance sweeping following the 2:1 resonance crossing will remove an additional $\sim$90–95% of them.

Thus, in summary, to evaluate the sweeping secular resonance model and the embedded planetary embryo model for the primordial excitation and clearing of the asteroid belt in the context of the Nice Model, the three criteria we will use are:

1. Can the model excite the eccentricities and inclinations of the primordial asteroid belt to values comparable to their current values?
2. Can the model deplete the primordial asteroid belt down to $\sim$10–20$\times$ its current mass before the LHB?
3. Can the model cause radial migration of asteroids comparable to the value inferred from the radial mixing of different asteroid taxonomic types?

In the following sections, we describe our modeling and analysis of the sweeping secular resonance model (Section 4) and the embedded planetary embryo model (Section 5), evaluating each model according to these three criteria.

4. Sweeping secular resonance model

4.1. Method

To model the effect of sweeping secular resonances driven by the depletion of the solar nebula on the asteroid belt, we have developed a modified version of the swift_rmvs3 integrator (Levison and Duncan, 1994), which we call swift_rmvs3_np, that can incorporate an additional time-varying potential, such as that due to a depleting solar nebula. As a closed-form analytic solution for the gravitational potential due to a realistic 3-D, axisymmetric solar nebula [e.g., the Hayashi (1981) minimum-mass solar nebula] does not exist, and numerical calculation of the potential for every body at every timestep would be computationally expensive, we adopt a simpler approach.

We first run a code that generates a set of data files giving the gravitational acceleration (A_r and A_z) over an axisymmetric grid of points in r and z due to an assumed solar nebula density profile. For uniform nebula depletion, in which the density of the nebula decreases with time but its profile stays the same, we need only generate a single file as the time-varying density can easily be taken into account in swift_rmvs3_np. For non-uniform depletion, where different regions of the nebula are depleted at different times, files are generated for a set of different times. Our swift_rmvs3_np code reads in these files and interpolates, using a bilinear interpolation scheme, over r, z (and in the non-uniform case, time t) to calculate A_r and A_z due to the solar nebula potential for each body at each timestep.

For the density profile of the solar nebula in our model, we assume the same profile as used by Nagasawa et al. (2000) [the Hayashi (1981) minimum-mass solar nebula], labeled here as $\rho_H(r,z)$. We test two idealized models of nebula depletion. The first is uniform depletion, in which the nebula density decays as

$$\rho(r,z,t) = \rho_H(r,z)e^{-t/\tau}, \tag{1}$$

where τ is the exponential decay timescale. The second is non-uniform depletion in which the nebula is cleared from the inside outwards according to

$$\rho(r,z,t) = \begin{cases} 0 & \left(r < r_{\mathrm{edge}}(t)\right), \\ \rho_H(r,z) & \left(r \geqslant r_{\mathrm{edge}}(t)\right), \end{cases} \tag{2}$$

with

$$r_{\mathrm{edge}}(t) = V_{\mathrm{edge}}t. \tag{3}$$

Here V_{edge} is the speed at which the inner edge of the nebula moves outwards. We assume that there are no gaps in the nebula around the orbits of the giant planets. In reality, Jupiter and probably Saturn would open small gaps in the nebula. The effect of such small gaps on secular resonance sweeping in the inner Solar System, however, is minimal (e.g., Nagasawa et al., 2000).

Our code generates input files for swift_rmvs3_np that give A_r and A_z over a grid of points spaced by 0.1 AU and ranging from 0 to 15 AU in r and 0 to 5 AU in z. The potential is calculated by integrating over the nebula from 0 to 20 AU in r and 0 to 7 AU in z. In the non-uniform case, a set of files is generated for different positions of the nebula edge spaced 0.1 AU apart. Increasing the resolution (e.g., using spacings smaller than 0.1 AU) or increasing the range over which the nebula is considered for calculating the potential has a negligible effect on our results.

Previous work on sweeping secular resonances did not take into account the self-gravity of the material in the asteroid belt region or inner Solar System, which can potentially affect the locations of secular resonances. While we treat the asteroids as massless test particles, we include the effects of self-gravity by including additional A_r and A_z terms due to the initial surface density profile $\sigma(r)$ of solid material in the early inner Solar System. We use an initial surface density profile that was able to reasonably reproduce the current terrestrial planets in the terrestrial planet accretion simulations of Chambers (2001) [also O'Brien et al. (2006)], where $\sigma(r) = \sigma_o(r/1\ \mathrm{AU})^{-3/2}$ with $\sigma_o = 8\ \mathrm{g\,cm^{-2}}$ for $r > 0.7$ AU, and $\sigma(r)$ decreases linearly from a maximum value at $r = 0.7$ AU to zero at 0.3 AU. This distribution is extended out to 4 AU, giving $\sim 4.7\ M_\oplus$ of material between 0.3 and 4 AU. This effect of this material is included in the same manner as the effect of the nebula potential, by reading a file of calculated A_r and A_z values into swift_rmvs3_np. Self-gravity is treated in all of our simulations unless explicitly noted.

A timestep of 9 days is used in all of our simulations, giving over 100 timesteps per orbit for a body with a of 2 AU. Test simulations we have performed show that this is more than sufficient to accurately resolve both the standard orbital evolution of the planets and test particles, as well as the effects of the nebula potential and self-gravity. Jupiter and Saturn (with their current masses of 318 and 95 $M_\oplus$) are included in all of our simulations and are allowed to interact with and perturb one-another, such that they will have small non-zero eccentricities even if they initially begin on circular orbits. Uranus and Neptune are not included in the simulation, as they have only a minor influence on the motion of Jupiter, Saturn and the bodies in the inner Solar System.

Nagasawa et al. (2000) found non-uniform inside-out clearing of the nebula to be the most effective at exciting both the eccentricities and inclinations of asteroids. Hence it represents a best-case scenario to test in our new simulations. They also found that uniform depletion is incapable of raising the inclinations of asteroids because the ν_{15} and ν_{16} resonances do not sweep through the main-belt region. We test that model again here in order to determine if this still holds true for the Jupiter and Saturn configuration in the Nice Model.

The effect of gas drag, which can affect the orbits of asteroid-sized bodies, especially when they become eccentric and experience high velocities relative to the gas, is not included in our model. As shown by Nagasawa et al. (2000) and confirmed in our simulations that follow, in the case of inside-out nebula depletion, secular resonances sweep through the asteroid belt after the nebula gas is gone from that region—hence, gas drag would not affect the asteroids after they become excited. In the case of uniform depletion, gas drag could potentially affect our results as some nebula gas will be present during the resonance sweeping, but it would only act to decrease the ability of uniform depletion to explain the current characteristics of the asteroid belt in the context of the Nice Model, as we explain in Section 4.2.

We have performed simulations to compare our model to that of Nagasawa et al. (2000) under the same initial conditions used in their work, and we obtain comparable results. Specifically, we find that in the case studied by Nagasawa et al. (2000) in which Jupiter and Saturn are on their present orbits and the solar nebula is on the ecliptic plane, we can achieve excitation of e and i comparable to the current values in the asteroid belt when the nebula is cleared from the inside outwards on a ~ 1 Myr timescale, comparable to observational estimates of the lifetimes of gas disks around solar-type stars (e.g., Strom et al., 1993; Zuckerman et al., 1995; Kenyon and Hartmann, 1995). When we use a more realistic model in which the nebula plane coincides with the invariant plane of Jupiter and Saturn, the excitation of inclinations is greatly diminished, as also found by Nagasawa et al. (2001, 2002).

A limitation of our model, which is also present in all previous work on sweeping secular resonances (see, e.g., Petit et al., 2002), is that the planets and other bodies are affected by the potential of the solar nebula, but the solar nebula is not perturbed by the planets. This is a necessary simplification, as accurately modeling the response of the nebula to planetary perturbations (and the response of the planets to the distorted nebula) would require a 3-D model of the dynamics of the nebula, which is beyond the scope of this work.

We performed several test simulations starting with the nebula on the invariant plane of Jupiter and Saturn. Since Jupiter and Saturn can respond to perturbations from the nebula but the nebula remains fixed, Jupiter and Saturn are quickly perturbed such that the nebula plane and the invariant plane of Jupiter and Saturn no longer coincide exactly, and are tilted relative to one another. The angle between them is $\sim 0.40°$ in the case where Jupiter and Saturn start on their present orbits, and $\sim 0.15°$ in the case where they start on the low-e, low-i orbits assumed in the Nice Model. For comparison, the ecliptic plane is tilted $\sim 1.6°$ relative to the Jupiter–Saturn plane in the current Solar System.

Thus, even when the solar nebula initially coincides with the invariant plane of Jupiter and Saturn in our simulations (and all previous simulations), a small angle between the nebula plane and the Jupiter–Saturn invariant plane will result, such that the simulations will only be an approximation to the idealized case. This is unlikely to have any effect on the eccentricity excitation of asteroids, as suggested by our own simulations and those of Nagasawa et al. (2001, 2002), as well as by analytical descriptions of the behavior of secular resonances (Morbidelli and Henrard, 1991). However, it can potentially have a significant effect on the inclination excitation of asteroids. Specifically, the ν_{15} resonance should not exist in the case where the nebula exactly coincides with the invariant plane. Thus, the small non-zero inclination between the nebula and invariant plane that results in our simulations will cause the ν_{15} resonance to have some effect, and hence to cause more inclination excitation that would in reality occur. The ν_{16} resonance would still exist even in the case where the nebula exactly coincides with the invariant plane, and hence any inclination excitation by the ν_{16} resonance that we find is a real effect.

4.2. Results

Fig. 1 shows the excitation of asteroids in e and i resulting from the inside-out depletion of a minimum-mass Hayashi (1981) nebula as described by Eq. (2). The asteroids initially have e and $\sin(i) \sim 0.01$, and Jupiter and Saturn are on the initial orbits predicted by the Nice Model (nearly circular and co-planar, and closer together than in their current configuration). The plane of the nebula initially coincides with the invariant plane of Jupiter and Saturn. The inner edge of the nebula is moved outwards from the Sun at a constant rate, and the clearing timescales given in the plot are the times required for the nebula edge to move from the Sun to 20 AU, at which point the secular resonance sweeping is essentially over in the asteroid belt and inner Solar System.

Previous simulations of inside-out nebula depletion assuming the current orbits of Jupiter and Saturn found that the ν_5, ν_6, ν_{15} and ν_{16} resonances all sweep inwards through the entire asteroid belt zone. In our simulations, assuming the initial planetary orbits predicted by the Nice Model, all of the resonances still sweep inwards and the ν_5 and ν_{15} resonances still sweep through the entire main belt (although, as discussed above, the ν_{15} should in reality not exist). However, the ν_6 stops at $\sim$3.4 AU and the ν_{16} stops at $\sim$2.6 AU (with no self-gravity, the ν_6 still ends in essentially the same position, while the ν_{16} stops at $\sim$3.4 AU). Note that these positions also roughly correspond to mean-motion resonances (MMR) with Jupiter, where 2.6 AU is the 3:1 MMR and 3.4 AU is the 2:1 MMR—these are shifted outwards relative to the current Solar System because Jupiter begins several tenths of an AU further from the Sun in the Nice Model. The primary reason that these secular resonances stop further from the Sun in the Nice Model than in the current Solar System configuration is that Jupiter and Saturn are closer together in the Nice Model, increasing one-another's orbital precession rates and thus increasing the Solar System eigenfrequencies corresponding to those secular resonances. Asteroids must therefore be located closer to Jupiter, which speeds up their precession, in order to have precession rates matching those eigenfrequencies.

Previous simulations assuming Jupiter and Saturn's current orbits found a significant excitation in both eccentricity and inclination of asteroids in the main belt zone, partly because the secular resonances all swept the entire main belt and also because the current eccentricities and inclinations of Jupiter and Saturn cause the secular resonances to be relatively strong. For example, Nagasawa et al. (2000) found that nebula clearing timescales of $\sim$1 Myr could boost the e and i of asteroids to their current values. However, as the resonances are much weaker with the nearly circular and co-planar Jupiter and Saturn predicted by the Nice Model, much longer nebula depletion times are necessary to achieve significant excitation in e and i in our simulations.

In our simulations, raising the eccentricities of asteroids to values comparable to their current values requires a nebula

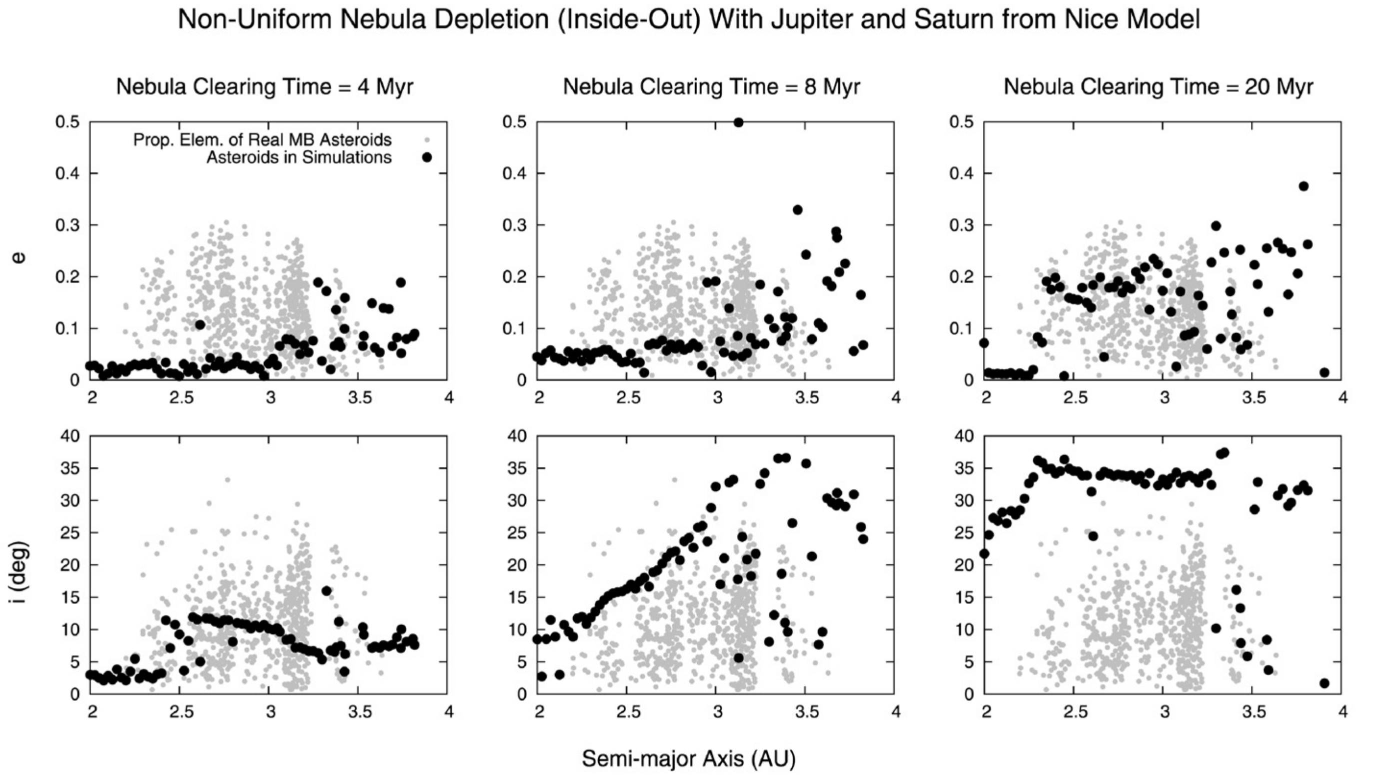

Fig. 1. Excitation of asteroids in e and i resulting from the inside-out clearing of a minimum-mass Hayashi (1981) nebula (Eq. (2)), compared to the actual proper elements of asteroids larger that ~50 km (Knežević and Milani, 2003). The solar nebula initially coincides with the invariant plane of Jupiter and Saturn, and Jupiter and Saturn are on the initial orbits predicted by the Nice Model. The asteroids initially have e and $\sin(i) \sim 0.01$. The clearing timescales are the times necessary for the inner edge of the nebula to move at a constant rate from the Sun to 20 AU, at which point the secular resonance sweeping is essentially over in the asteroid belt region. The secular resonances sweep through the asteroid belt after the gas is dissipated in that region. Hence, gas drag from the nebula will not affect the orbits of the asteroids in this simulation.

dissipation timescale of 10–20 Myr, which is longer than the typical lifetime of disks ($\lesssim$10 Myr, e.g., Strom et al., 1993; Zuckerman et al., 1995; Kenyon and Hartmann, 1995). Inclinations are excited to their present values in less than 10 Myr in our simulations. However, the inclination excitations we find are likely an overestimate. As noted in Section 4.1, the presence of the ν_{15} resonance in our simulations is a result of the fact that the nebula in our model perturbs the planets but is not perturbed in return, such that a small angle is introduced between the nebula and the invariant plane. In the case where the nebula and invariant plane exactly coincide, there should be no ν_{15} resonance to excite inclinations. The effect of the ν_{16} resonance that we find is still real, but the ν_{16} resonance stops at ~2.6 AU and hence cannot excite inclinations in the inner main belt.

There is very little radial migration of any of the asteroids in these simulations, as secular resonances only influence e and i. Likewise, while we do not treat gas drag, it should have a minimal effect on the radial migration of asteroids since the nebula gas is cleared from the asteroid belt before the resonance sweeping, and hence will be gone once the asteroids become eccentric (eccentric asteroids are the most strongly affected by gas drag). In addition, very few bodies are excited enough to be driven out of the belt—even for the longest clearing timescale, 20 Myr, only 8 bodies out of the initial 81 are removed from the belt. These are all outer-main-belt bodies that have their eccentricities raised to Jupiter-crossing values. Hence, in the context of the Nice Model, the inside-out depletion model is not able to cause significant semi-major axis mobility or mass depletion in the asteroid belt, and it is difficult to obtain excitation of e and i throughout the entire main belt that is comparable to the current values for asteroids on timescales consistent with the observationally-inferred nebula depletion timescales for solar-type stars.

Fig. 2 shows the excitation of asteroids in e and i resulting from the uniform depletion of a minimum-mass Hayashi (1981) nebula with a timescale $\tau = 5$ Myr (Eq. (1)). The asteroids initially have e and $\sin(i) \sim 0.01$, and Jupiter and Saturn are on the initial quasi-circular orbits predicted by the Nice Model. The solar nebula initially coincides with the invariant plane of Jupiter and Saturn, and these simulations are carried out to 12.5τ, or 62.5 Myr. While previous work assuming the current orbits of Jupiter and Saturn (Heppenheimer, 1980; Ward, 1981; Lecar and Franklin, 1997; Nagasawa et al., 2000) find that the inclination resonances do not sweep through the asteroid belt in the uniform depletion case, we find that with the initial orbits of Jupiter and Saturn predicted by the Nice Model, the ν_{16} resonance sweeps outwards to ~2.6 AU and can thus affect the inner part of the asteroid belt (with no self-gravity, it sweeps outwards to ~3.4 AU). The ν_{15} resonance never appears, as also found in previous simulations with the current orbits of Jupiter and Saturn. The ν_5 and ν_6 resonances both sweep inwards, with

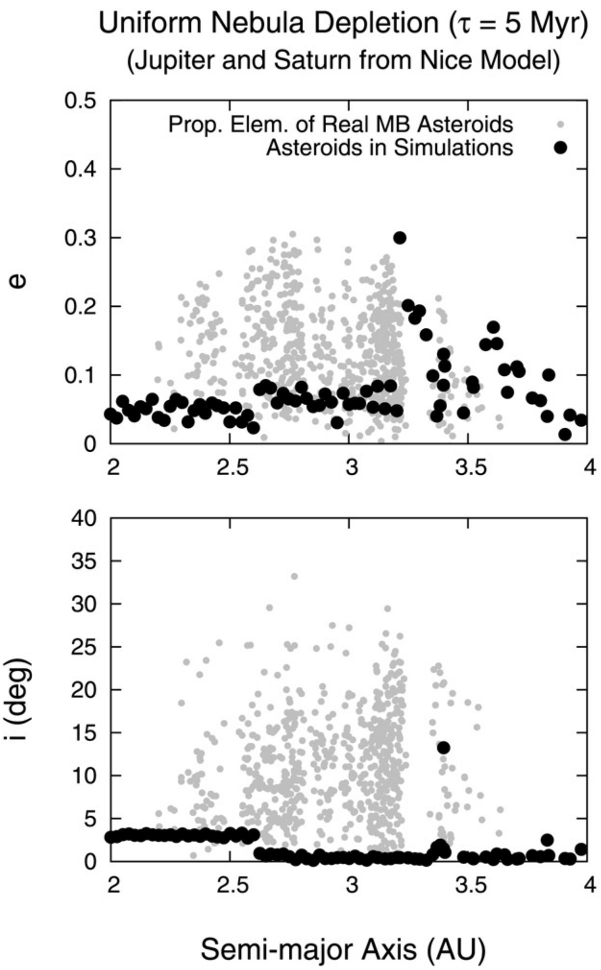

Fig. 2. Excitation of asteroids in e and i resulting from the uniform depletion of a minimum-mass Hayashi (1981) nebula with a timescale $\tau = 5$ Myr (Eq. (1)). The solar nebula initially coincides with the invariant plane of Jupiter and Saturn, and Jupiter and Saturn are on the initial orbits predicted by the Nice Model. The asteroids initially have e and $\sin(i) \sim 0.01$. In this simulation, there will still be some gas in the asteroid belt region while the secular resonances sweep through the region. The effect of that remnant gas is described in the text.

the ν_5 passing through the entire main belt and the ν_6 stopping at ~3.4 AU (it stops at essentially the same location in the case with no self-gravity).

Even for $\tau = 5$ Myr, excitation of e and i in the asteroid belt is small compared to the current values, and both e and i are not excited throughout the entire main belt region. Since τ is an exponential decay timescale, a τ of 5 Myr implies that it would take ~20 Myr for the nebular gas to decay to 1% of its original density. Hence, it seems unlikely that uniform depletion can excite e and i in the asteroid belt to values comparable to their current values on a timescale consistent with observational estimates of the lifetimes of gas disks around solar-type stars (Strom et al., 1993; Zuckerman et al., 1995; Kenyon and Hartmann, 1995).

While we do not treat gas drag in these simulations, it could potentially lead to some semi-major axis mobility in the uniform depletion case since gas will be present in the asteroid belt region during and in the time after the resonance sweeping occurs and boosts the eccentricities. Likewise, it could potentially lead to some depletion of material from the asteroid belt. However, gas drag will act to damp the eccentricity and inclinations of asteroids, such that the already low e and i resulting from sweeping secular resonances will be lowered even further. Hence, in the context of the Nice Model, some depletion and semi-major axis mobility of asteroids might result from the uniform depletion of the solar nebula, but the excitation of e and i in the asteroid belt occurs only over a limited range of a and gives e and i well below their present values, for depletion timescales consistent with observational estimates.

In summary, in the context of the Nice Model, it is difficult to explain the observed characteristics of the asteroid belt solely by secular resonance sweeping during the depletion of the solar nebula. For extremely long nebula dissipation timescales (compared to the observed lifetimes of protoplanetary disks), inside-out nebula depletion can potentially yield dynamical excitation comparable to the current asteroidal e and i (although exciting i inside of ~2.6 AU requires that the nebula plane and invariant plane do not coincide exactly), such that part of the asteroid belt could potentially survive the sweeping secular resonances driven by outer planet migration during the LHB. However, even in that extreme case, there would still be little radial migration of asteroids and little dynamical depletion of material from the asteroid belt.

Likewise, in the case of uniform depletion of the solar nebula, even for long depletion timescales, e and i are not strongly excited in the asteroid belt, and i is not excited at all outside of ~2.6 AU. Gas drag could potentially lead to some semi-major axis mobility of asteroids and provide some mass depletion, but with the long timescales involved, e and i would be damped back to near-zero. Hence, neither the uniform nebula depletion model nor the non-uniform, inside-out depletion model would be able to satisfy the three constraints outlined at the end of Section 3.

The final issue we address in this section is the effect of sweeping secular resonances on the terrestrial planet region. As noted previously, the ν_5 resonance sweeps past the inner edge of the asteroid belt and into the terrestrial planet region. Nagasawa et al. (2000), Kominami and Ida (2004), Lin (2004), and Nagasawa et al. (2005a, 2005b) have suggested that ν_5 sweeping during uniform nebula depletion could boost protoplanet eccentricities, leading to orbit crossing and mergers that would form terrestrial planets, and that tidal damping by the remnant nebula gas would then damp the final planets' eccentricities to their current values. Note that eccentricity excitation would also occur in the case of inside-out depletion, but there would be no nebular gas in the terrestrial planet region to damp the final planets' eccentricities back down. As the ν_5 resonance would sweep through the asteroid belt and all the way to ~0.6 AU, given the current orbits of Jupiter and Saturn, this mechanism could conceivably affect the entire terrestrial planet region. To explore how this scenario would be affected if Jupiter and Saturn were initially on the orbits predicted by the Nice Model, we performed an additional set of simulations extending the particle population into the terrestrial planet region. Remember that in our simulations we take the potential due to the self-gravity of the particles into account, so that the locations of secular res-

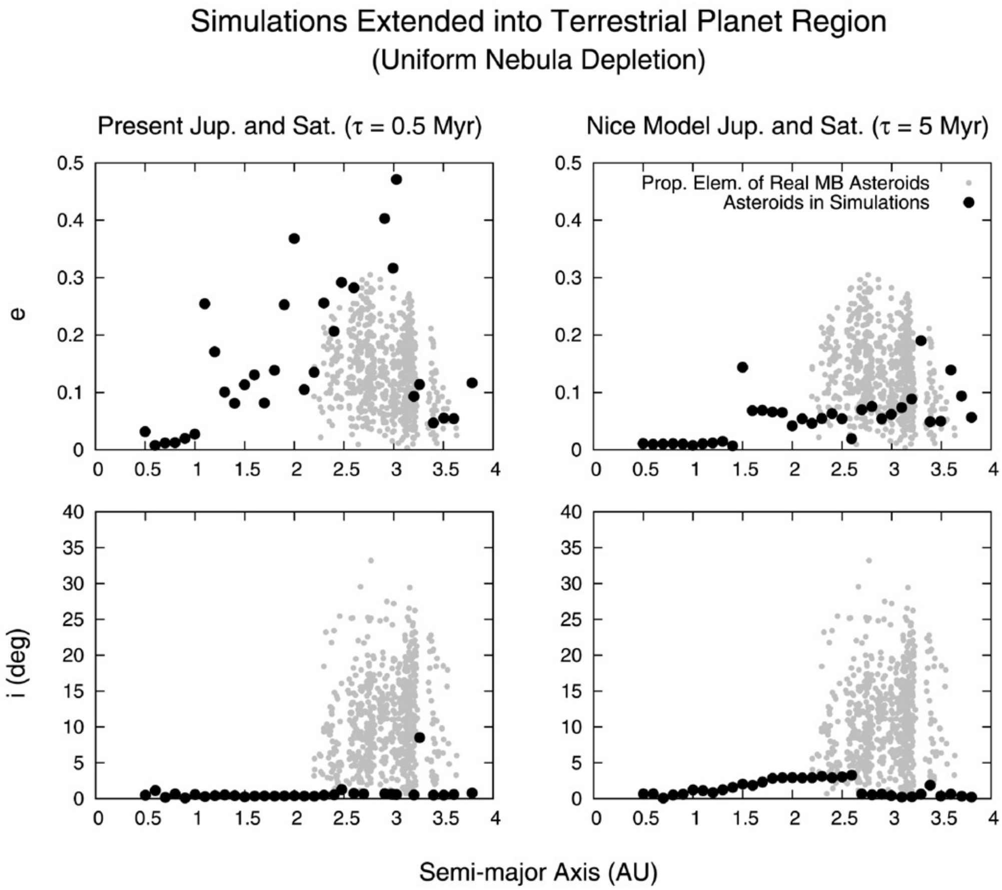

Fig. 3. Excitation of test particles in e and i throughout the entire inner Solar System for different orbits of Jupiter and Saturn. We assume the uniform depletion of a minimum-mass Hayashi (1981) nebula according to Eq. (1), and the solar nebula coincides with the invariant plane of Jupiter and Saturn. The particles initially have e and $\sin(i) \sim 0.01$. On the left are the final orbital elements of the test particles assuming the present orbits of Jupiter and Saturn and $\tau = 0.5$ Myr. On the right are the final orbital elements of the test particles assuming the initial orbits of Jupiter and Saturn predicted by the Nice Model and $\tau = 5$ Myr. The primary difference between the two simulations is that the ν_5 resonance, which excites eccentricity, stops at $\sim$0.6 AU with the current planetary configuration but stops at $\sim$1.5 AU with the planetary configuration predicted by the Nice Model, which has Jupiter and Saturn closer to one another, hence forcing faster precession of one another's longitudes of perihelion.

onances are evaluated correctly. We assume the surface density of solid material in the inner Solar System discussed in Section 4.1 (based on Chambers, 2001), which is consistent with that required to build a system of $\sim$2 Earth-mass planets.

Fig. 3 shows the effect of uniform nebula depletion throughout the entire inner Solar System in the case where Jupiter and Saturn are on their present orbits ($\tau = 0.5$ Myr) and in the case where they are on the orbits predicted by the Nice Model ($\tau = 5$ Myr). In both cases, the invariant plane of Jupiter and Saturn initially coincides with the plane of the solar nebula. In the present orbit case, we reproduce the result that the ν_5 sweeps inwards to $\sim$0.6 AU. In the case where Jupiter and Saturn are on the orbits predicted by the Nice Model, we find that the ν_5 stops at $\sim$1.5 AU instead of sweeping the full terrestrial planet region. Again, this is because Jupiter and Saturn are closer together than in their current configuration. Thus the precession rate of Jupiter is faster and consequently the ν_5 resonance is located further out. Gas drag was not included in our simulations, but would have little effect on the orbital evolution of protoplanets, which would be on the order of 1000 km or more in diameter.

While we have not explored in detail the effects of sweeping secular resonances on the accretion of terrestrial planets, these results show that terrestrial planet formation models that rely on secular resonance sweeping can be profoundly affected by the orbits of Jupiter and Saturn in the early history of the Solar System. For example, from Fig. 3, eccentricities of protoplanets would be excited closer to the Sun than the present orbit of Venus in the case where Jupiter and Saturn are on their present orbits, while in the case where Jupiter and Saturn begin on the orbits predicted by the Nice Model, there would be no eccentricity excitation of any protoplanets in the Venus and Earth region. We stress that this result does not depend on the specific initial conditions of the Nice model, in particular on the ratio of the orbital periods of Saturn and Jupiter being smaller than 2. Simply assuming Jupiter and Saturn on closer orbits, even with a ratio of orbital periods larger than 2 as in Malhotra (1993, 1995), would lead to a similar result that the ν_5 resonance would not sweep the entire terrestrial planet region. Hence, models that require secular resonance sweeping in the terrestrial planet region should consider the possibility that Jupiter and Saturn did not originate on their current orbits.

5. Embedded planetary embryo model

5.1. Method

The most recent work on this model, originally proposed by Wetherill (1992), is Petit et al. (2001). Due to computational limitations, Petit et al. (2001) could not perform direct numerical integrations of a system of fully-interacting planetary embryos and asteroids. Instead, they used a modified version of swift_rmvs3 (Levison and Duncan, 1994) that reads in the results of previous numerical integrations of the dynamics of planetary embryos during the terrestrial planet formation process (Wetherill and Chambers, 1997; Chambers and Wetherill, 1998). The code then uses these results to numerically integrate a population of massless asteroids under the influence of the embryos. The Petit et al. (2001) work used the most advanced simulations possible with the computers available at the time and, as such, was a ground-breaking demonstration of the effects of planetary embryos on the primordial asteroid belt. However, given the current availability of substantially more powerful computers, we seek to improve upon that work with more realistic simulations. In addition, we wish to explore the effects that the initial orbits of Jupiter and Saturn in the Nice Model would have on the dynamics of the embryos and, in turn, on the primordial sculpting of the asteroid belt.

For our simulations, we use SyMBA (Duncan et al., 1998), which is a symplectic N-body integrator that handles close encounters. SyMBA allows for a population of gravitationally interacting massive bodies as well as a population of less-massive bodies that interact with the massive bodies but not with one another. In addition, when two bodies collide, they are merged together, conserving linear momentum. Hence, it is an ideal tool for modeling a system in which there is a relatively small number of massive planetary embryos and a much more numerous population of less-massive planetesimals, such as the primordial asteroid belt. Simulations of the early stages of planetary accretion (e.g., Kokubo and Ida, 1998) suggest that the primordial asteroid belt would likely consist of a population of lunar- to Mars-mass planetary embryos embedded in a roughly equal mass of much smaller planetesimals. The current asteroid belt consists of the remnants and fragments of those planetesimals.

In our simulations, we use an initial distribution of planetary embryos and planetesimals based on that of Chambers (2001) (their simulations 21–24). The surface density profile of the distribution is $\sigma(r) = \sigma_o(r/1\ \mathrm{AU})^{-3/2}$ with $\sigma_o = 8\ \mathrm{g\,cm^{-2}}$ for $r > 0.7$ AU, and $\sigma(r)$ drops linearly from a maximum at 0.7 AU to zero at 0.3 AU. We place half of the mass in large, 0.0933 $M_\oplus$ embryos, which is roughly the mass of Mars, and the other half of the mass in planetesimals 1/40 as massive [Chambers (2001) used a factor of 1/10]. These planetesimals serve as tracers for the asteroid population, and the term 'asteroids' will be used interchangeably with planetesimals in the subsequent discussions. Their initial eccentricities and inclinations are randomly chosen from 0–0.01 and 0–0.5°, respectively. This distribution is extended out to 4 AU [the Chambers (2001) simulations were truncated at 2 AU], and the total mass in the disk is $\sim$4.7 $M_\oplus$. 11 Embryos and $\sim$450 planetesimals lie outside of 2 AU, with a total mass of $\sim$2.1 $M_\oplus$. Because the embryos interact with the planetesimals, our simulations include the effects of *dynamical friction*, in which the equipartition of energy between small and large bodies in a gravitationally interacting population leads to the damping of the relative velocities (e and i) amongst the large bodies (e.g., Wetherill and Stewart, 1989, 1993). Our results are therefore likely to be more realistic than previous simulations that included smaller numbers of interacting bodies or embryos that are unaffected by the asteroids. The final outcomes of our simulations, for what concerns the formation of the terrestrial planets, are discussed in O'Brien et al. (2006). The terrestrial planet systems that we obtain are a better match to the real Solar System than those formed in previous, lower-resolution simulations.

For comparison, the embryo simulation used in the Petit et al. (2001) work (namely 2C from Chambers and Wetherill, 1998) begins with 56 embryos from 0.5 to 4 AU spaced a constant number of mutual Hill radii apart. The embryos vary in mass as $a^{3/2}$, such that embryos at 2, 3, and 4 AU have masses of 0.13, 0.24, and 0.37 $M_\oplus$, respectively, and the total mass of embryos is 5 $M_\oplus$. There are no smaller planetesimals such as those in our initial distribution. That simulation produces 2 planets, a 1.3 $M_\oplus$ planet at 0.68 AU with e and i of 0.15 and 5°, and a 0.48 $M_\oplus$ planet at 1.5 AU with e and i of 0.03 and 23°, which is substantially different from our Solar System as well as the final planetary systems formed in Chambers (2001) and, in particular, in O'Brien et al. (2006). Moreover, in the Petit et al. (2001) work, the planetary embryos continually excite the asteroids via gravitational interactions, but are not damped in any way because the asteroids are treated as massless test particles. Hence, we expect that integrations using our new initial distribution and accounting for dynamical friction will provide a better match to the actual behavior of bodies in the primordial asteroid belt.

While we expect that our initial distribution will yield a significantly more accurate and physically realistic result than that used in previous simulations, primarily because of dynamical friction due to the many small planetesimals, we note that it could be varied in several ways that could give somewhat different results than those presented here. Increasing or decreasing the fraction of the total mass placed in the planetesimal population would correspondingly increase or decrease the damping effects of dynamical friction on the embryos. Similarly, we chose a planetesimal/embryo mass ratio of 1/40, as a compromise between having a number of bodies that could be integrated in a reasonable time and having an accurate treatment of dynamical friction. Using a larger number of correspondingly less massive planetesimals would likely give a somewhat more accurate treatment of the effects of dynamical friction and potentially more realistic results, although such simulations would be computationally intensive. Finally, rather than assuming that all embryos are roughly Mars-mass, we could use a larger number of smaller embryos, or, as predicted by some embryo formation models (e.g., Kokubo and Ida, 2000), a distribution where embryo mass increases with distance from the Sun. Performing a suite of simulations spanning the full range of possible initial distributions is beyond the scope of the work presented here, although a comparison of our results with those of previous simulations can illustrate some of the dependencies that our results may have on the initial distribution, as we discuss further in Section 5.2.3.

We performed two sets of 4 simulations with our initial planetesimal and embryo distribution, using different random number seeds to generate the specific orbital parameters in each of the simulations. The simulations were run for 250 Myr each, and a timestep of 7 days was used. In the case of close encounters between bodies, not including the Sun, SyMBA switches to an adaptive-timestep method in order to accurately resolve the encounter. The major limitation of the SyMBA algorithm is that it is not able to treat close encounters with the Sun. Hence, bodies with a perihelion less than 0.1 AU were assumed to hit the Sun and were discarded. Furthermore, those with an aphelion greater than 10 AU (i.e., crossing both Jupiter and Saturn) were assumed to be ejected from the system. Each simulation required roughly 1 month of computing time on an Opteron workstation.

In our primary set of simulations, denoted here as CJS1-4 (for 'Circular Jupiter and Saturn'), we adopt the initial orbits of Jupiter and Saturn that were found by Gomes et al. (2005) to best reproduce both the current orbits of the outer planets and the timing of the Late Heavy Bombardment in the Nice Model, as described in Section 3. In order to determine which of the differences between our simulations and the Petit et al. (2001) simulations are due to using different Jupiter and Saturn orbits and which are due to other effects such as dynamical friction and the use of a different initial distribution of bodies, we performed a second set of simulations, denoted here as EJS1-4 (for 'Eccentric Jupiter and Saturn'). In those simulations, we use the present orbits of Jupiter and Saturn, and the embryos and planetesimals follow the same distribution as in the CJS simulations and are centered on the invariant plane of Jupiter and Saturn. We note that it is unlikely that Jupiter and Saturn formed on their current, eccentric and inclined orbits, as outer planet formation models (e.g., Pollack et al., 1996; Lubow et al., 1999) tend to form planets on circular orbits, and it is not clear that planet–disk interactions are capable of exciting the eccentricities and inclinations of Jupiter- and Saturn-mass planets (e.g., Papaloizou et al., 2001; D'Angelo et al., 2006; Kley and Dirksen, 2006).

Jupiter and Saturn are included from the beginning in all of our simulations. Petit et al. (2001) found that the difference between simulations in which Jupiter and Saturn are present at the beginning of the simulation and those in which they are added after 10 Myr is negligible, at least in terms of the magnitude and rate of dynamical excitation and depletion of asteroids following the introduction of Jupiter and Saturn, which is our primary concern in this work. In fact, before the introduction of Jupiter, the orbital excitation that the asteroids receive from the embryos is not enough to provide a significant dynamical depletion of the belt. However, this excitation could trigger collisional comminution in the belt, so that the late introduction of Jupiter and Saturn would likely lead to a larger integrated amount of collisional activity in the asteroid belt.

In all of our simulations, we used a 7-day timestep, which is common in the literature for this type of simulation using SyMBA or similar integrators such as Mercury (Chambers, 1999), and we assume that any bodies with a perihelion less than 0.1 AU hit the Sun. However, we realized in retrospect that such a timestep was likely too large. In general, SyMBA and similar integrators require a timestep that is less than $\sim 1/20$ of the orbital period at the perihelion distance if the perihelion passage is to be resolved accurately (Levison and Duncan, 2000). For a 7-day timestep, bodies with a perihelion distance smaller than 0.5 AU may therefore not be resolved correctly in our simulations, or in other published simulations using similar integrators with comparable timesteps.

Since embryos in our simulations, for the most part, remain relatively dynamically cold, few are likely to suffer close perihelion passages. Those that do are primarily those that enter the 3:1 or ν_6 resonance and are driven into the Sun, which happens quickly enough that numerical errors have little effect. However, some planetesimals, even if not in a resonance, may be kicked onto low-perihelion orbits by encounters with the embryos and remain on those orbits long enough that errors may build up. The effect of this is that those bodies have their semimajor axes raised to Jupiter-crossing values and are ejected from the system. Hence, the primary effect of a too-large timestep is that some fraction of planetesimals were likely artificially ejected from our systems, giving an effect similar to setting the perihelion cutoff to a larger value. Even though this may happen on occasion, we believe that the overall effect of this process will be small, especially since it is much more likely to affect bodies in the inner terrestrial planet region than those in the asteroid belt region.

5.2. Results

In each of our 8 simulations, a stable system of terrestrial planets is formed within 250 Myr. The properties of these terrestrial planet systems are described in detail in O'Brien et al. (2006). In 7 out of 8 cases, no planets are formed substantially outside of 2 AU (although a few form just outside of 2 AU, such that the asteroid belt region is compressed relative to that in our Solar System). However, in simulation EJS2, a small planet consisting of just a single embryo and a few planetesimals remains around 3.2 AU.

We define the 'asteroid belt region' in each simulation based on the position of Jupiter and the outermost terrestrial planet (the pseudo-Mars) formed in the simulation (although in simulation EJS2, the second-furthest planet, rather than the small planet at 3.2 AU, is considered to be the pseudo-Mars, otherwise the asteroid belt in that simulation would be essentially non-existent). Jupiter's semi-major axis is 5.45 AU in the CJS simulations and 5.2 AU in the EJS simulations. The semimajor axis of the pseudo-Mars is generally on the order of 1.5–2 AU, and is systematically larger in the CJS simulations compared to the EJS simulations. If an asteroid's perihelion is within 0.1 AU of the aphelion of the pseudo-Mars or its aphelion is within

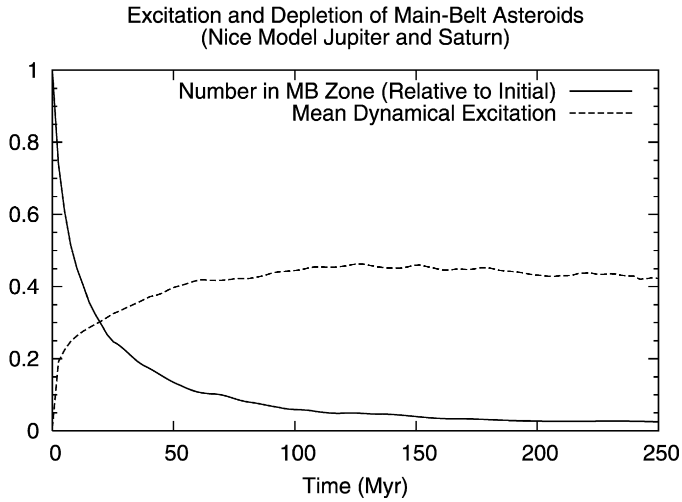

Fig. 4. Fraction of asteroids in the main-belt region as a function of time in the embedded planetary embryo model, summed from all four of our simulations that have Jupiter and Saturn on the orbits predicted by the Nice Model (the CJS simulations). Also plotted is the mean dynamical excitation $\langle\sqrt{e^2+\sin^2(i)}\rangle$ as a function of time.

1 AU of the perihelion of Jupiter, it is deemed unstable. Furthermore, we consider the outer edge of the asteroid belt to be the 3:2 mean-motion resonance with Jupiter ($a = 4.16$ AU in the CJS simulations and 3.97 AU in the EJS simulations). This is reasonably consistent with the range of stability of the asteroid belt in our Solar System.

We reiterate that the primary purpose of our simulations is to determine if the embedded planetary embryo model is capable of explaining the current state of the asteroid belt in the context of the Nice Model, as described in Section 3. Hence, in Section 5.2.1 we only present the results of our CJS simulations (those with the initially circular and co-planar Jupiter and Saturn) and discuss their match with the current state of the asteroid belt. We reserve the discussion of the differences between the CJS simulations, EJS simulations and Petit et al. (2001) work for Section 5.2.2. Finally, in Section 5.2.3 we discuss the possible dependencies that our results may have on our choice of the initial planetesimal and embryo distribution.

5.2.1. *Simulations for the Nice Model*

Fig. 4 shows the instantaneous number of asteroids present in the main belt region in our CJS simulations, as a fraction of the number initially present in that region. This is obtained by averaging the results of all four simulations. The decay is roughly exponential, and at the end of 250 Myr, the population instantaneously present in the asteroid belt region is reduced to 2.5% of its original number. For the individual simulations, the remaining fractions are 2.2, 5.5, 2.2, and 0.6%, respectively.

These instantaneous values do not account for the fact that some of the asteroids might spend part of their time outside the stable region and are unlikely to survive to the present day. When we analyze the remaining asteroids in more detail by looking over a 1 Myr window, only 2.1% of the original number are solidly confined to the stable region. For the individual simulations, the remaining stable fractions are 2.0, 5.0, 1.3, and 0.4%, respectively.

We can compare the depletion in our CJS simulations to the amount of depletion necessary to explain the current state of the asteroid belt. Our CJS simulations start with ~2.1 $M_\oplus$ of material outside of 2 AU. Half of this mass is in embryos, which are all removed from the belt, and the other half is in asteroids, of which roughly 2% survive on stable orbits. Thus, of the original mass in the asteroid belt in our simulations, roughly 1% survives, namely 0.02 $M_\oplus$. This corresponds to roughly 10–20 times the current mass in the belt, which is one of the requirements for matching the current state of the asteroid belt in the context of the Nice Model, as explained in Section 3.

Fig. 4 also shows the mean dynamical excitation $\langle\sqrt{e^2+\sin^2(i)}\rangle$ of the remaining asteroids as a function of time in our CJS simulations. The dynamical excitation increases rapidly to ~0.2 right at the beginning, then slowly increases to ~0.45 over the next 100 Myr and remains at that level for the remainder of the simulation. For the asteroids that remain entirely within the stable region over a 1 Myr window, the mean dynamical excitation is 0.39. For the actual asteroid belt, the mean dynamical excitation of all asteroids larger than 50 km in diameter is 0.24, calculated using the proper element catalog of Knežević and Milani (2003).

Fig. 5 shows the 1-Myr averaged orbital elements of the final stable asteroids in our four simulations with Jupiter and Saturn on the orbits predicted by the Nice Model (CJS), plotted against the proper elements of all asteroids larger than 50 km in diameter (from Knežević and Milani, 2003). The match in eccentricity is quite good—the final stable asteroids in our simulations have a mean eccentricity of 0.156, compared to 0.135 for the actual asteroids. The lack of bodies in the inner main belt is most likely due to the fact that the pseudo-Mars formed in our simulations is always more massive than the real Mars and in 3 out of 4 cases has a larger semimajor axis than the real Mars.

The inclinations are systematically larger in our simulations than in the actual asteroid belt, with a mean i of 20.8° compared to 10.9° for the real asteroids. This is the primary cause of the larger dynamical excitation in our CJS simulations compared to the actual asteroid belt, as noted above. This may indicate that important effects may be missing from our model, or that higher resolution simulations or a different initial planetesimal and embryo distribution are necessary. Interestingly, though, the fact that such high-inclination bodies are produced in the CJS simulations could potentially help to produce the current populations of high-inclination asteroids such as the Hungarias and Phocaeas.

As discussed in Section 3, when Jupiter and Saturn cross their mutual 2:1 MMR in the Nice Model and migrate to their final orbits, secular resonances sweep through the asteroid belt region, which reshuffles the asteroid e and i distribution and drives many of the asteroids from the belt. Since embedded planetary embryos can give an initial excitation of the asteroid belt roughly comparable to the current belt, 5–10% of the asteroids will be able to survive the crossing of the 2:1 resonance by Jupiter and Saturn. This secondary depletion, in addition to

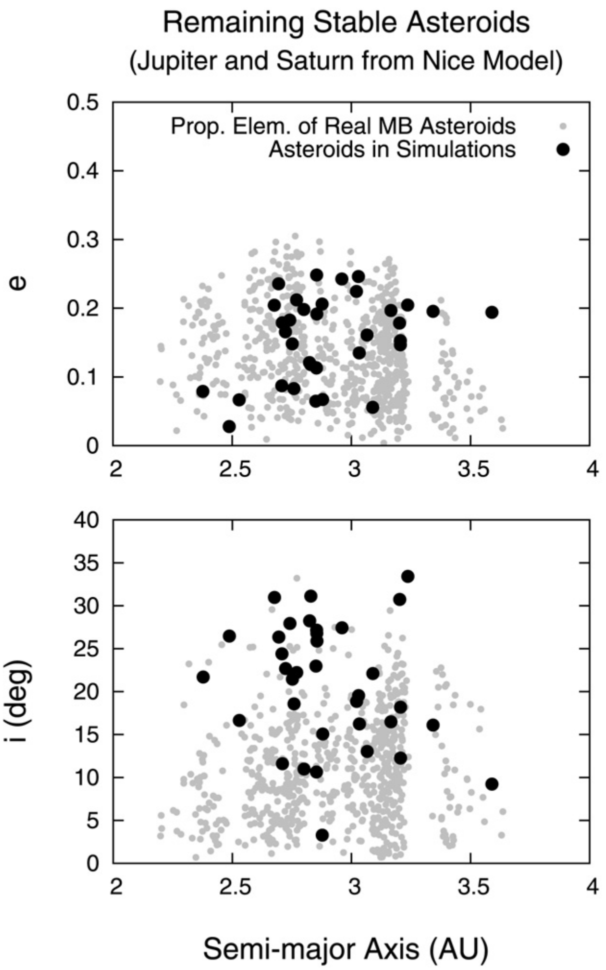

Fig. 5. 1-Myr averaged orbital elements of remaining asteroids from all four of our simulations of the embedded planetary embryo model that have Jupiter and Saturn on the orbits predicted by the Nice Model (the CJS simulations), compared to the actual proper elements of asteroids larger that ∼50 km (Knežević and Milani, 2003).

the depletion due to the embedded planetary embryos described above, is sufficient to explain the current mass of the asteroid belt relative to its estimated primordial mass. The orbital distribution of asteroids following the 2:1 resonance crossing will likely be comparable to the orbital distribution before the 2:1 resonance crossing, and hence roughly comparable to the current orbital distribution of asteroids, although a more accurate determination of the distribution following the 2:1 resonance crossing requires additional simulations that are beyond the scope of this paper.

Asteroids in our simulations experience substantial radial migration due to encounters with the more massive embryos. Fig. 6 shows a histogram of the $|\Delta a|$ of the final stable asteroids in our CJS simulations relative to their positions at the beginning of the simulations. The mean $|\Delta a|$ is 0.68 AU and the median is 0.50 AU. It is difficult to quantify exactly how much radial migration has occurred in the actual asteroid belt, although from the radial distribution of different asteroid taxonomic types, Gradie and Tedesco (1982) estimate that they are mixed over a scale of ∼1 AU, which is reasonably consistent with the results of our CJS simulations.

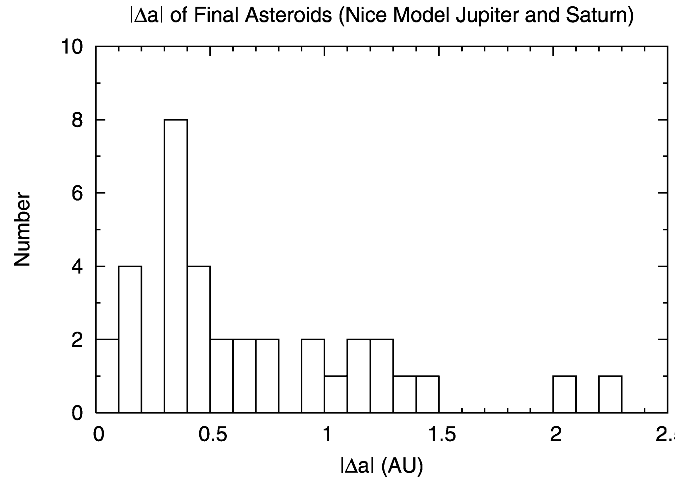

Fig. 6. Histogram of the migration in semi-major axis of the final asteroids in all four of our simulations of the embedded planetary embryo model that have Jupiter and Saturn on the orbits predicted by the Nice Model (the CJS simulations). The mean $|\Delta a|$ is 0.68 AU and the median is 0.5 AU.

A significant number of our asteroids have $|\Delta a|$ on the order of 1 AU and a few as large as 2 AU. This is comparable to or larger than the width of the asteroid belt, implying that these asteroids are likely 'interlopers,' namely that they formed outside of the asteroid belt and were emplaced in the belt by the scattering action of the embryos. Looking at those asteroids that are fully confined to the stable region over a 1 Myr window, 40% of asteroids remaining in the CJS simulations are interlopers.

Of the final stable asteroids in our CJS simulations, 0.0, 5.7, and 34% originate from between 0.3–1.0, 1.0–1.5, and 1.5 AU to the inner edge of the asteroid belt (which is defined by the position of the outermost terrestrial planet formed in each of the individual simulations). These interlopers lie a mean (and median) distance of 0.6 AU from the inner edge of the asteroid belt. Only a single asteroid from beyond the 2:1 MMR with Jupiter enters into a stable orbit inside the 2:1 (2.9% of final stable asteroids). This is a possible origin of primitive asteroids such as Ceres in the current main belt.

Bottke et al. (2006) studied in detail the injection of interlopers into the main belt from the inner Solar System. Bottke et al. (2006) find that 0.01–0.1, 0.8–2, and ∼10% of bodies originating from 0.5–1, 1–1.5, and 1.5–2 AU, respectively, end up in the main belt. Of bodies originating from those same zones in our CJS simulations, we find that 0, 1.1, and 4.5%, respectively, end up on stable orbits in the asteroid belt, reasonably consistent with Bottke et al. (2006). As noted by Bottke et al. (2006), asteroids originating from the inner Solar System are a likely candidate for differentiated asteroids such as Vesta, as well as the parent bodies of iron meteorites.

In summary, the embedded planetary embryo model is able to satisfy all 3 criteria discussed in Section 3 in the context of the Nice Model. It is able to (1) dynamically excite the asteroid belt to a level comparable to its current dynamical excitation, such that ∼5–10% of asteroids will be able to survive the sweeping of secular resonances following Jupiter and Saturn's crossing of their mutual 2:1 MMR; (2) it is able to deplete the original mass of the asteroid belt down to ∼10–20× the current

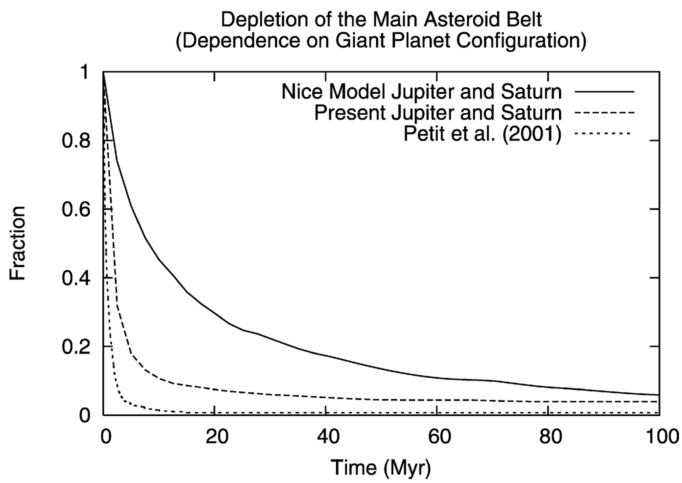

Fig. 7. Comparison of the rate of clearing of the asteroid belt by embedded planetary embryos in the different sets of simulations. Top curve is for our four simulations in which Jupiter and Saturn are on the orbits predicted by the Nice Model (CJS), the middle curve is for a similar set of four simulations that we performed in which Jupiter and Saturn are on their present orbits (EJS), and the lowest curve is from Simulations A1–A3 of Petit et al. (2001).

mass; and (3) it is able to give significant semi-major axis mobility to asteroids, consistent with the observed radial mixing of different taxonomic types in the actual asteroid belt. In the following section, we compare the results of the CJS simulations described here with the Petit et al. (2001) work and our EJS simulations, both of which assume the current orbits of Jupiter and Saturn.

5.2.2. *Comparison to other simulations*

Fig. 7 compares the number of asteroids, as a fraction of the initial number present, as a function of time in our CJS simulations, EJS simulations, and the Petit et al. (2001) simulations. The curves are only plotted to 100 Myr to emphasize the differences at the beginning of the simulations. The number of asteroids on stable orbits in the asteroid belt at the end of our CJS simulations (250 Myr) is 2.1% of the original number, and for the EJS simulations it is 3.0% (4.1% if we ignore the simulation in which an embryo remains in the belt). In the Petit et al. (2001) work, it is 0.7%. The rate of depletion is largest in the Petit et al. (2001) simulations and smallest in the CJS simulations, while the absolute depletion is largest in the Petit et al. (2001) and smallest in the EJS simulations. These values are summarized in Table 1.

Of bodies originally residing in the asteroid belt, the CJS simulations have the largest fraction of planetesimals accreted into planets, while the Petit et al. (2001) simulations have the least. Conversely, the Petit et al. (2001) simulations have the most planetesimals either being ejected from the system or hitting the Sun, while the CJS simulations have the least. As for the fates of embryos originally residing in the main belt, the EJS simulations have larger fractions, compared to the CJS simulations, that are ejected from the system or hit the Sun, and smaller fractions being accreted into planets or accreted onto another embryo and then lost from the system. The fates of planetesimals and embryos lost from the asteroid belt are summarized in Tables 2 and 3.

All of these trends have the same explanation. In the CJS simulations, the embryos are less excited but stay in the belt longer, possibly migrating inwards and accreting onto a terrestrial planet, while in the EJS simulations the embryos are more excited and tend to leave the system more quickly, by colliding with the Sun or being ejected by Jupiter, given the stronger resonances with the eccentric Jupiter and Saturn. The embryos' larger excitations lead to faster depletion of planetesimals in the EJS simulations than in the CJS simulations, while the fact that embryos are around longer in the belt in the CJS simulations leads to more overall depletion in the final asteroid population.

Table 1
Comparison of our CJS and EJS simulations and those of Petit et al. (2001) (their simulations A1–A3, and A4, D2, E2 and F2 for the interloper fraction)

	CJS	EJS	Petit et al.
Remaining fraction	2.1%	3.0% (4.1%)	0.7%
Excitation	0.39	0.24 (0.23)	0.35
Mean Δa (AU)	0.68	0.31	0.24
Median Δa (AU)	0.50	0.28	0.20
Interloper fraction	40%	8.2%	–

All values given for our CJS and EJS simulations are only for asteroids that are stable over a 1-Myr window, and values in parentheses exclude the case where an embryo remains in the belt at the end of the simulation (EJS2).

Table 2
Fates of the original planetesimals residing in the asteroid belt region at the beginning of our simulations

	CJS		EJS		Petit et al. (2001)	
	2:1	3:2	2:1	3:2	A1	A3
Ejected from system	72.6%	77.0%	40.0%	55.8%	26%	36%
Hit Sun	5.1%	4.1%	46.0%	33.1%	72%	61%
Accreted into planets	17.6%	14.6%	10.9%	7.7%	2%	3%
Accreted then lost	4.7%	4.3%	3.1%	3.4%	–	–

This does not include planetesimals that may have originated outside of the asteroid belt region and wandered into it. Values are calculated for our simulations assuming the outer edge of the asteroid belt region is at the 3:2 resonance with Jupiter (our nominal definition) as well as the 2:1 resonance. 'Accreted then Lost' refers to bodies that are first accreted by another body before being ejected from the system or hitting the Sun. In Petit et al. (2001) Simulation A1, the asteroids are originally distributed from 2–4 AU and in A3, from 2–2.8 AU. Bodies that were accreted and lost in the Petit et al. (2001) simulations were not listed separately.

Table 3
Same as Table 2, but for the original embryos residing in the asteroid belt region at the beginning of our simulations

	CJS		EJS	
	2:1	3:2	2:1	3:2
Ejected from system	35.5%	38.5%	41.1%	54.9%
Hit Sun	0.0%	0.0%	20.5%	15.7%
Accreted into planets	51.6%	48.7%	33.3%	25.5%
Accreted then lost	12.9%	12.8%	5.1%	3.9%

The values for the Petit et al. (2001) simulations are not given here as they were only reported for all of the embryos in their simulations, rather than just for those originating in the asteroid belt, and were given as mass fractions since their embryos had a-dependent masses, thus making comparison to our results difficult.

The Petit et al. (2001) simulations, like our EJS simulations, considered an eccentric Jupiter and Saturn. The differences in the outcomes of these simulations [faster and stronger asteroid depletion in the Petit et al. (2001) simulations] can be explained by the facts that in Petit et al. (2001), the embryos in the asteroid belt are individually more massive, they are more excited because there is no dynamical friction to damp them, and they remain longer in the inner asteroid belt ('a few times 10 My' compared to a median residence timescale of 10 Myr in our EJS simulations). The more rapid elimination of embryos from the main belt in the EJS simulations compared to the Petit et al. (2001) simulations is likely due to the fact that our planetesimals can gravitationally interact with the embryos. While in the Petit et al. (2001) simulations the embryos could only be knocked into resonances by embryo–embryo encounters, in our simulations the planetesimals could provide a large number of additional small kicks to embryos, more efficiently pushing them into resonances.

The Δa of the remaining asteroids, relative to their initial position, is largest in the CJS simulations and smallest in the Petit et al. (2001) simulations (see Table 1). The difference between the CJS and EJS simulations is, again, due to embryos being around longer in the CJS simulations, thus allowing for a larger number of encounters with the asteroids. The main difference with Petit et al. (2001) is likely due to the initial conditions: As most of their asteroids started between 2 and 4 AU or 2 and 2.8 AU in their simulations, few surviving bodies could be displaced more than the asteroid belt width.

Petit et al. (2001) performed a few simulations with asteroids initially in the 1–2 AU range (but none initially in the belt), and found that 3 objects out of 400 ended up in the main belt. For comparison, we get 5 interlopers out of 334 started between 1 and 2 AU in our EJS simulations and 14 in our CJS simulations. Hence, it appears that the injection rate of bodies into the main belt from the 1–2 AU range in the Petit et al. (2001) simulations (0.75%) is somewhat lower than in our EJS (1.5%) and significantly lower than in our CJS simulations (4.2%). We form no Hilda asteroids (those in a 3:2 resonance with Jupiter) in our CJS simulations, and form 2 in the EJS simulations (3.3% of the total number of stable asteroids). Petit et al. (2001) form 1 Hilda in their simulations A1 and A2 out of 7 total stable asteroids (14%). It is likely that all of these differences could be due at least in part to small number statistics.

It is interesting to note that both the CJS and EJS simulations imply that there must have been a secondary depletion event of roughly an order of magnitude at some point, most likely coinciding with the LHB, since in neither case are the embryos alone able to deplete enough mass from the asteroid belt to match its current mass. If Jupiter and Saturn began on their current eccentric orbits (which, as discussed previously, is unlikely), then without a mechanism to explain the secondary mass depletion event in the asteroid belt, the embedded planetary embryo model is not able to provide sufficient mass depletion. In contrast, in the Nice Model (i.e. our CJS simulations), the secondary depletion event naturally occurs when Jupiter and Saturn cross their mutual 2:1 mean-motion resonance, which triggers the LHB and drives 90 to 95% of the asteroids existing at the time out of the main belt (see Section 3).

It is also important to note that the ejection of planetesimals and embryos from the inner Solar System, primarily by Jupiter, causes the orbits of Jupiter and Saturn to change (this would occur in addition to, or in the absence of, any orbital change driven by a disk of trans-neptunian planetesimals). In the EJS simulations, Jupiter migrates inwards by $\sim$0.025 AU, its initial e of $\sim$0.05 decreases to $\sim$0.01, and its initial i of $\sim 0.35°$ (relative to the invariant plane) decreases to $\sim 0.025°$. There is negligible change in a for Saturn, but like Jupiter, its e and i also decrease to similarly low values. The timescale for these changes is on the order of 50 Myr. Thus, as also noted by other researchers (e.g., Petit et al., 2001; Chambers and Cassen, 2002), if no other mechanisms are invoked to enhance the eccentricity and inclination of Jupiter and Saturn, they must start out with e and i larger than their present values by about a factor of two in order to end up in their current configuration, and as noted previously, there are currently no well-defined mechanisms to form planets that are initially as eccentric as the current Jupiter and Saturn, much less twice as eccentric.

In contrast, as Jupiter and Saturn's e and i are initially very low in the CJS simulations, there is negligible change in those values for either planet, although Jupiter migrates inwards by $\sim$0.025 AU. Jupiter and Saturn's orbits thus begin and remain essentially circular and co-planar throughout the simulations. This does not pose a problem in the context of the Nice Model, however, as they would be boosted to their current e and i hundreds of Myr later when they cross their mutual 2:1 mean-motion resonance.

5.2.3. *Effect of the initial planetesimal and embryo distribution*

While it was computationally prohibitive to test a range of initial planetesimal and embryo distributions, the comparison of our CJS and EJS simulations with the Petit et al. (2001) simulations illustrates some of the dependencies that our results may have on the choice of the initial distribution. Varying these parameters in future simulations may help us achieve a better fit of our models to observations, e.g., reconciling the large asteroid inclinations in our CJS simulations with the observed asteroid orbital distribution. However, varying several different parameters can potentially change the same observable quantity, and changing a single parameter can potentially affect multiple observable quantities, such that finding the ideal set of parameters is not necessarily a straightforward process.

The fraction of the total mass placed in planetesimals in our simulations is 50%, which is a reasonable fraction based on simulations of embryo formation (e.g., Kokubo and Ida, 1998), and in the Petit et al. (2001) simulations it is zero percent. This is one of the primary reasons that the Petit et al. (2001) simulations give a more rapid and pronounced depletion of the asteroid belt—the embryos are not damped by dynamical friction. While the actual planetesimal mass fraction is unlikely to be zero, it may in reality be somewhat lower or higher than the 50% that we use, and varying this parameter could influence the rate and degree of depletion of the asteroid belt by changing the degree of damping of the embryos by dynamical friction. In addition, the presence of a significant population of small planetesimals likely helps to push embryos into resonances and drive them out of the main belt, as evidenced by the shorter residence times of embryos in the inner main belt in the EJS simulations compared to the Petit et al. (2001) simulations, noted in Section 5.2.2.

Another possibility is using an embryo distribution with masses that increase with distance from the Sun (e.g., Kokubo and Ida, 2000), which would place a smaller number of more massive embryos in the main belt than in our distribution, or using a distribution consisting of lunar-mass embryos, which are smaller than the Mars-mass embryos used in our distribution. A comparison of our EJS simulations with the Petit et al. (2001) simulations, which have more massive embryos in the asteroid belt, suggests that higher-mass embryos could contribute to more rapid and pronounced depletion of the asteroid belt, although this effect is difficult to disentangle from the effect of having no dynamical friction in the Petit et al. (2001) simulations.

A final parameter that could be varied in the initial distribution is the planetesimal/embryo mass ratio. We use a planetesimal/embryo mass ratio of $1/40$, which was chosen as a compromise between having a number of bodies that could be integrated in a reasonable amount of time and having a fine enough resolution to give an accurate treatment of dynamical friction. The primary effect of using a larger number of correspondingly smaller planetesimals would be a more accurate treatment of dynamical friction, which would result in the embryos being less dynamically excited and could potentially slow the rate and reduce the degree of dynamical depletion of asteroids. However, beyond a certain point, a limit would be reached where dynamical friction is accurately resolved and further increases in resolution would not lead to further changes. The fact that the terrestrial planets produced using our distribution (see O'Brien et al., 2006) are damped by dynamical friction to values of e and i comparable to their current values suggests that we are close to the resolution where dynamical friction is being resolved with reasonable accuracy.

We feel that there is a generally good agreement between our simulations and the observational and theoretical constraints on the asteroid belt's evolution. Varying the initial planetesimal and embryo distribution within a reasonable range of parameters will likely lead to somewhat different results than what we present here, but in turn may allow us to tune our model and obtain an even better fit to the constraints.

6. Summary and discussion

We have performed new simulations to study and compare two models for the excitation and depletion of the primordial asteroid belt in the context of the Nice Model (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005), in which Jupiter and Saturn began on nearly circular and co-planar orbits that were closer together than in their current configuration. We find that sweeping secular resonances driven by the depletion of the primordial solar nebula (e.g., Heppenheimer, 1980; Ward, 1981; Lemaitre and Dubru, 1991; Lecar and Franklin, 1997; Nagasawa et al., 2000) are unable to match all of the observed characteristics of the current main belt, namely its large dynamical excitation, the radial mixing of different asteroid taxonomic types, and its large mass depletion relative to its initial mass. At best, eccentricities can be boosted throughout the asteroid belt in the case of inside-out nebula depletion, but only for nebula depletion timescales that are significantly larger than the lifetimes of disks observed around other solar-type stars.

Several authors (e.g., Nagasawa et al., 2000; Kominami and Ida, 2004; Lin, 2004; Nagasawa et al., 2005a, 2005b) have proposed scenarios in which the sweeping of the ν_5 secular resonance through the terrestrial planet region could aid terrestrial planet formation by increasing the eccentricities of embryos in that region, leading to orbit crossing and mergers. In extending our simulations into the terrestrial planet region, we find that for the initial orbits of Jupiter and Saturn predicted by the Nice Model, the ν_5 secular resonance only sweeps inwards as far as 1.5 AU, rather than to its current position of $\sim$0.6 AU. Thus, in the case of the Nice Model (or in any model with Jupiter and Saturn closer together than in their current configuration), ν_5 sweeping would not occur throughout most of the terrestrial planet region, and thus would not strongly influence terrestrial planet accretion.

In contrast to sweeping secular resonances, planetary embryos embedded in the primordial asteroid belt, exciting and scattering one-another and the asteroids into resonances with Jupiter and Saturn (e.g., Wetherill, 1992; Chambers and Wetherill, 1998; Chambers and Wetherill, 2001; Petit et al., 2001), are able to reasonably reproduce all of the observed characteristics of the asteroid belt in the context of the Nice model—mass depletion, dynamical excitation, and radial mixing. The mass depletion due to the embryos alone is roughly 10–20 times less than that necessary to explain the current mass of the asteroid belt relative to its initial mass. However, as explained in Section 3, when Jupiter and Saturn cross their mutual 2:1 mean-motion resonance in the Nice Model, there is a secondary depletion by a factor of 10–20 that, in addition to the depletion due to embedded planetary embryos, will give a final mass of the asteroid belt comparable to its current mass.

Interestingly, even in the case where Jupiter and Saturn begin on their current orbits, the mass depletion due to embedded planetary embryos is still a factor of 10–20 times less than necessary to explain the current mass of the asteroid belt. Thus, a secondary depletion event is required regardless of the initial orbital configuration of Jupiter and Saturn. Such a secondary depletion event is a natural consequence of the Nice Model, but additional mechanisms would have to be invoked if Jupiter and Saturn began in their current orbital configuration.

The inclinations of asteroids at the end of our embedded planetary embryo simulations are systematically larger, by about a factor of two, than those in the current asteroid belt. It is possible that many of those high-inclination asteroids would be eliminated during the secondary depletion event in the Nice Model, or that they would help to produce the current populations of high-inclination asteroids such as the Hungarias and Phocaeas. It is also possible that some parameters, such as the mass and orbital distribution assumed for the planetary embryos, would need to be changed in order to give a better fit. Testing these hypotheses in detail would require additional simulations that are beyond the scope of this work. The fact that the orbital distribution produced in our single set of simulations is reasonably consistent with the current orbital distribution of asteroids suggests that the fit will likely improve in future simulations.

To summarize our results and place them in the overall context of Solar System history and evolution, we envision a scenario in which Jupiter and Saturn began on quasi-circular orbits and were closer to each other, and the asteroid belt was inhabited by both asteroids and planetary embryos. Because of the orbital configuration of Jupiter and Saturn, when the nebular gas went away during the first few Myr of Solar System history, only the ν_5 secular resonance was able to sweep through the entire belt, and it had little effect on the asteroids. Over the following ∼10–100 Myr, the mutual perturbations amongst the embryos and the resonant gravitational effects of Jupiter and Saturn drove all embryos out of the belt. In the process, most of the asteroids left the belt as well (although some interlopers entered from the inner Solar System), leaving the belt depleted down to a few percent of its initial mass. The surviving asteroids had orbits with distributions of e and i comparable to the current distribution, but were about 10–20 times more numerous than the current main belt objects.

After ∼600 Myr of slow migration driven by interactions with the massive planetesimal disk beyond Neptune, Jupiter and Saturn crossed their mutual 2:1 mean-motion resonance. This event changed the structure of the Solar System, with the orbits of Jupiter and Saturn acquiring their current eccentricities and the two planets migrating towards their current orbits over a few tens of Myr. Consequently, the ν_6 and ν_{16} resonances swept through the belt, ejecting ∼90–95% of the asteroids existing at that point. These escaping asteroids were the impactors most responsible for the Late Heavy Bombardment of the Moon (Strom et al., 2005). The asteroids surviving this second episode of secular resonance sweeping (roughly a tenth of a percent of those initially present in the asteroid belt region) are the current main belt asteroids, with a total mass, orbital excitation, and degree of radial mixing comparable to those currently observed.

The fact that the primordial asteroid belt was significantly more massive than the current main belt has important implications for its collisional history. An asteroid population that is initially massive and undergoes a dynamical depletion event in addition to collisional evolution for a given time, say 4.5 Gyr, evolves to the same final state as a population that does not experience an initial, massive phase and undergoes collisional evolution for a longer 'pseudo-time' (Bottke et al., 2005a). The pseudo-time quantifies the amount of collisional evolution that has occurred, accounting for enhanced collisional activity in an initially more massive population. Bottke et al. (2005a) find that the current asteroid size distribution is best reproduced after a pseudo-time of ∼7.5–9.5 Gyr, and Bottke et al. (2005b) show that this is consistent with the degree and rate of depletion of the primordial asteroid population found by Petit et al. (2001).

A preliminary calculation based on our simulations of embedded planetary embryos in the asteroid belt in the context of the Nice Model (the CJS simulations from Section 5), assuming that Jupiter forms at 3 Myr and that there is a secondary depletion by a factor of 10–20 when Jupiter and Saturn cross their mutual 2:1 MMR after ∼600 Myr, gives a pseudo-time of 19–34 Gyr. This is substantially larger than the estimate of ∼7.5–9.5 Gyr from Bottke et al. (2005a), and implies a larger total amount of collisional activity than in the Bottke et al. (2005a) simulations. Bottke et al. (2005a) also estimate that 2 impacts capable of forming Vesta's large crater would occur over a pseudo-time of 27 Gyr, although given the stochastic nature of large impacts, it is possible that even for a pseudo-time of 34 Gyr, only one impact would occur on Vesta, such that the latter is not a strong constraint.

Reconciling the long collisional pseudo-time implied by our simulations with the much shorter estimates of Bottke et al. (2005a) will likely require a re-evaluation of both the collisional modeling of Bottke et al. (2005a) and the dynamical simulations presented here. Our simulations may still lack the resolution necessary to give a fully accurate description of the dynamical depletion of the primordial asteroid belt. Similarly, a different choice of the planetesimal and embryo masses and orbital distribution could significantly change the depletion rate and hence the collisional pseudo-time. In the collisional modeling, it is possible that changing the assumed strength law for asteroids could give a similar final size distribution for a longer collisional pseudo-time, and hence be more consistent with our dynamical simulations. Likewise, it is possible that the effects of large, stochastic breakup events dominate the evolution of the size distribution and could be primarily responsible for its current shape. For example, Bottke et al. (2005a) find that even though shorter pseudo-times tend to provide the best fit on average in the large set of simulations they ran, stochastic breakups can occasionally give a good fit at pseudo-times as late as 20 Gyr. Future work will focus on exploring these issues in more detail in order to build a more complete and self-consistent picture of the combined collisional and dynamical evolution of the asteroid belt.

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