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The Primordial Excitation and Clearing of the Asteroid Belt

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In this paper, we use N-body integrations to study the effect that planetary embryos spread between ∼0.5 and 4 AU would have on primordial asteroids. The most promising model for the formation of the terrestrial planets assumes the presence of such embryos at the time of formation of Jupiter. At the end of their runaway growth phase, the embryos are on quasi-circular orbits, with masses comparable to that of the Moon or Mars. Due to gravitational interactions among them, and with the growing Jupiter, their orbits begin to cross each other, and they collide, forming bigger bodies. A general outcome of this model is that a few planets form in a stable configuration in the terrestrial planet region, while the asteroid belt is cleared of embryos. Due to combined gravitational perturbations from Jupiter and the embryos, the primordial asteroids are dynamically excited. Most of the asteroids are ejected from the system in a very short time, the dynamical lifetime being on the order of 1 My. A few asteroids (less than 1%) survive, mostly in the region 2.8–3.3 AU, and their eccentricity and inclination distribution qualitatively resembles the observed one. The surviving asteroids have undergone changes in semimajor axis of several tenths of an AU, which could explain the observed radial mixing of asteroid taxonomic types. When the distribution of massive embryos is truncated at 3 AU, we obtain too many asteroids in the outer part of the belt, especially too many Hildas. This suggests that the formation of Jupiter did not prohibit the formation of large embryos in the outer belt and Jupiter did not accrete them while it was still growing. © 2001 Academic Press

Key Words: **asteroids, origin; Solar System, planetary embryos.**

I. INTRODUCTION

Recent observations, together with the development of new computational techniques and computers in the past few years, have launched a renewed interest in the study of the origin and early evolution of our Solar System. In the present paper, we investigate a scenario that tends to reproduce the observed characteristics of the asteroid belt. The asteroids represent a negligible fraction of the mass of the planets, but we believe that their large number means that they carry statistically significant clues for understanding the early evolution of our Solar System.

We now review the most important characteristics of the asteroid belt. In order to determine these, we have considered only asteroids with diameters larger than 50 km, for the following reasons. During the 4.5 Gyr of existence of the Solar System, the asteroids have evolved greatly through high-velocity collisions. Collision velocities are typically a few kilometers per second, very often resulting in the complete shattering and disruption of the colliding bodies. Therefore, most of the asteroids we see today are not primordial, but fragments of larger asteroids destroyed in a collision. Only the largest asteroids retain characteristics that relate to the formation of the asteroid belt and were not drastically changed by the later evolution. For this reason we consider only asteroids with diameters $D > 50$ km. These asteroids have collisional lifetimes on the order of the age of the Solar System or longer. Most of these are primordial asteroids; i.e., they were already present in the belt at the end of the excitation and mass depletion of the belt, when the terrestrial planets were completely formed. Note, however, that some of these objects could be fragments from gigantic collisions between embryos during the very early phases. The few large bodies that were destroyed generally yielded at most one large fragment (larger than 50 km), with mostly unchanged dynamical characteristics, and a swarm of smaller fragments (Tanga *et al.* 1999) In addition, it is very likely that we have discovered all the asteroids larger than 50 km; the completeness size is currently assumed to be about 35 km. So our statistics are not contaminated by observational biases. From Fig. 1a, we can naturally distinguish three zones: the *inner belt*, with $a < 2.5$ AU (3 : 1 mean motion resonance with Jupiter), the *central belt*, at $2.5 < a < 3.28$ AU (2 : 1 resonance), and the *outer belt*, beyond 3.28 AU. In the outer belt, all asteroids beyond 3.8 AU are in mean motion resonances with Jupiter.

The most striking features of the asteroid belt that one would like to explain with a unitary model are as follows:

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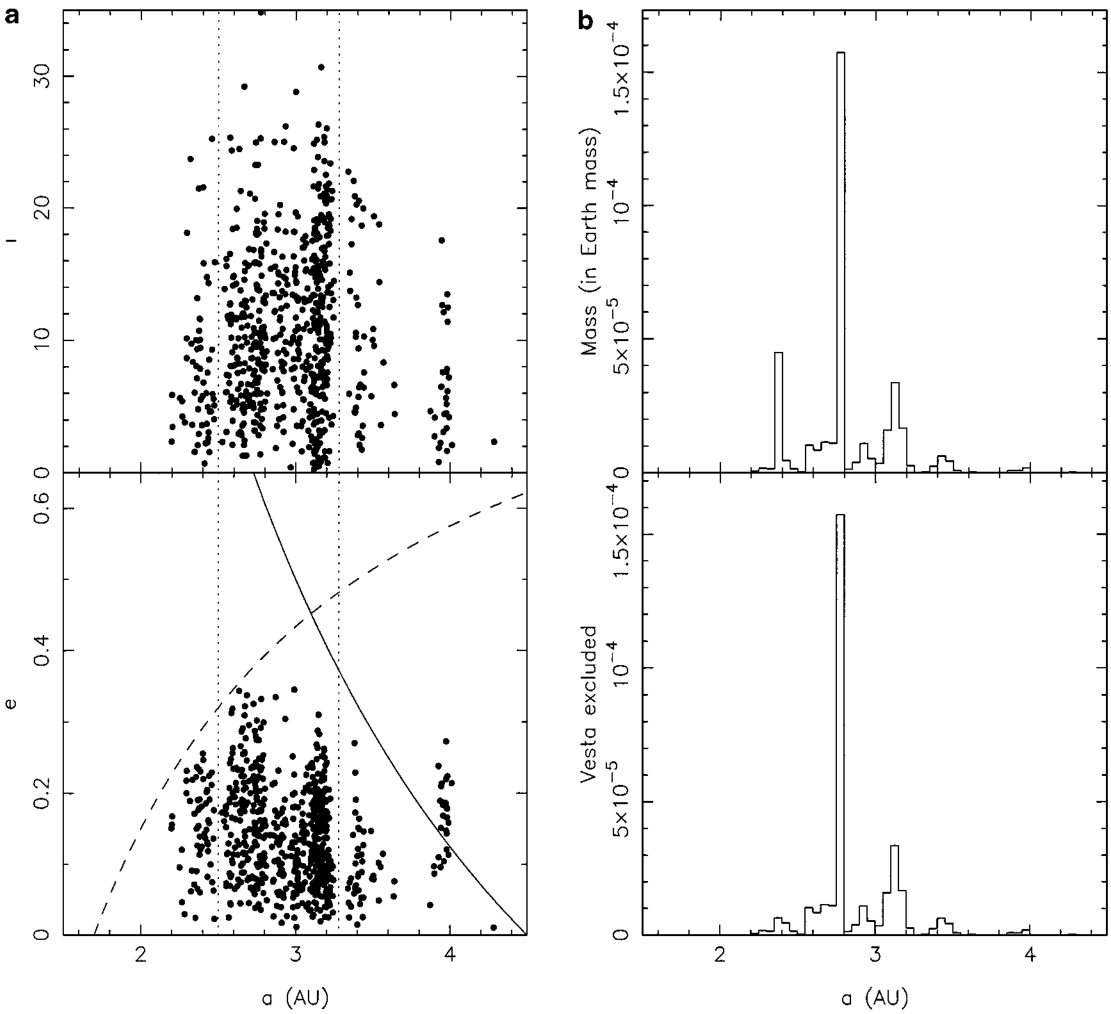

FIG. 1. (a) Osculating inclination (top) and eccentricity (bottom) versus semimajor axis for the asteroid belt for bodies larger than 50 km in diameter (solid line: aphelion distance at 4.5 AU; dashed line: perihelion distance at 1.7 AU). (b) Mass distribution of asteroids versus semimajor axis for all asteroids larger than 50 km (top) and excluding Vesta (bottom). The dotted lines give the boundaries of the inner belt (left), central belt (middle), and outer belt (right). This diagram has been drawn from Bowell's asteroid database (ftp.lowell.edu/pub/elgb/astorb.dat.gz). We used the sizes provided in this database. When no size was given, we used the absolute magnitude H, the albedo P_v, and the relation $D = 10^{(6.244-0.4H-\mathrm{Log}P_v)/2}$. The albedo was estimated according to the taxonomic type: 0.2 for types K, M, and S; 0.4 for types A and E; 0.05 for types C, D, F, and G; 0.12 otherwise. The density is also chosen depending on the taxonomic type: 1.5 for types C, D, E, G, and K; 2.5 for types A, E, and S; 3.5 for types M, R, and V.

(*i*) *Its strong dynamical excitation.* The median eccentricity and inclination of the bodies larger than 50 km are 0.15 and 6°, respectively, in the inner belt; 0.14 and 10.7° in the central belt; and 0.1 and 12.1° in the outer belt. In the outer belt, the median eccentricity is lower than that in the other parts because of instabilities due to Jupiter that tend to deplete the region above the solid line in Fig. 1a, with the exception of the bodies in the 3 : 2 and 4 : 3 resonances. The eccentricities and inclinations of the asteroids are much larger than those of the planets in our Solar System and much larger than those required for accretion of these bodies to take place.

(*ii*) *Its large mass depletion.* The present total mass of the asteroid belt is estimated to be of order $5 \times 10^{-4}\ M_\oplus$ ($M_\oplus$ = Earth mass), namely 10^3–10^4 times smaller than its primordial mass (Weidenschilling 1977). From Fig. 1b, we see that the mass deficiency is larger in the inner and outer belts than in the central part.

(*iii*) *The radial mixing of asteroid types.* The optical properties of the asteroids depend roughly on their distance from the Sun: S-types dominate the inner belt, C-types are the most abundant in the central belt, while P-types dominate in the outer belt, with the exception of the Trojan population, which is mainly D-type. However, the boundaries between compositional zones are not sharp: Asteroids of different types are mixed over scales ~1 AU (Gradie and Tedesco 1982). See Petit *et al.* (1999) for a more detailed presentation of these characteristics and their implications.

Several scenarios have been proposed to explain the asteroid belt; see the Introduction in Petit *et al.* (1999) for a brief review of those published up to 1998. In their paper, Petit *et al.* (1999) revisited and quantified an idea first proposed by Safranov (1979) and examined further by Wetherill (1989): that the asteroid belt was sculpted by the gravitational action of massive protoplanets (on the order of an Earth mass, $M_\oplus$) initially present in the Jupiter region and scattered by the giant planet once it accreted its gaseous envelope, the so-called Jupiter scattered planetesimals. Petit *et al.* (1999) found that this scenario is unlikely to reproduce the characteristics of the observed asteroid belt.

At the same time, more work has been done on another scenario: the sweeping of resonances across the primordial asteroid belt. For example, Franklin and Lecar (2000) have improved their model of the dispersion of the solar nebula. During this dispersal, test particles are subjected to secular resonance sweeping and to gas drag. However, the results of these authors do not explain the inclinations observed in the asteroid belt. Meanwhile, Nagasawa and co-workers (2000) have tried to solve the problem of inclination excitation by changing the way the nebula is dissipated. They showed that a nonuniform depletion is needed, i.e., an outward migration of the inner edge of the nebula, or a gap opening beginning at Jupiter's orbit. Their results are not encouraging: The asteroidal inclinations are all of the same order, not spread over a wide range as is the case for the asteroid belt. In addition, these authors found a mass loss that hardly exceeds a factor of $1/2$, and they found no radial mixing.

None of these models is able to explain in a completely satisfactory way the sculpting of the asteroid belt. Wetherill (1992) alternatively proposed an extension of the standard model of planetary accretion in which the asteroid belt was originally a massive dynamically cold system, which contained about 200 sublunar to martian size planetary embryos among its population. These embryos then excited and depleted the asteroid belt before being eliminated from that region due to their mutual gravitational interactions and the influence of Jupiter. Wetherill and Chambers (1997), using direct N-body simulations, have shown that the elimination of all embryos from the asteroid belt is dynamically plausible, while Chambers and Wetherill (2001) have shown that this mechanism is effective for a wide variety of initial conditions. Extending the disk of embryos into the terrestrial planet region, Chambers and Wetherill (1998) showed that this scenario is actually one of the most promising for the formation of terrestrial planets through high-velocity collisions of embryos. Recently, Morbidelli *et al.* (2000a) have shown that the presence of massive embryos in the asteroid belt may help explain some of the cosmochemical characteristics of the terrestrial planets.

In the present work, we assume that this scenario represents the situation during the formation of the terrestrial planets, and we estimate the effect of gravitational scattering by all these embryos on the asteroids. We start with data for the orbital evolution of the embryos obtained by Chambers and Wetherill (1998, 2001) and Chambers (1998). Given the orbital evolution of the giant planets and the embryos, we use the same modified version of the SWIFT_RMSV3 code (Levison and Duncan 1994) that Petit *et al.* (1999) used to calculate the time evolution of test particles representing the asteroids. As will be seen in Section II, the exact dynamical state of the asteroid belt after the dissipation of the nebula is not a crucial point. The dynamical effects we are describing in the present paper are unavoidable. It should be kept in mind that this model for terrestrial planet accretion still exhibits some differences from the actual planetary system. In particular, the final eccentricities and inclinations differ systematically. Hence we do not expect the model to reproduce the asteroid belt in a precise quantitative way, but rather we demonstrate a mechanism that seems to provide qualitatively satisfactory results.

The next Section (II) is devoted to the description of the results of our "nominal" simulation, while Section III summarizes the results from other simulations. We discuss the relevance of all the results, and the open problems, in Section IV.

To fix notations, throughout the paper we use "embryos" to refer to massive bodies which have not yet reached planet size, and "test particles," "particles," or "asteroids" to refer to members of the asteroid belt with negligible mass.

II. THE RESULTING ASTEROID BELT IN OUR REFERENCE SIMULATION

The starting point of our study is the end of the runaway growth phase of planetary embryos. At this point, embryos that are probably the size of the Moon or Mars have formed. These move in nearly circular, coplanar orbits. Further growth of the planets will occur through high-velocity collisions between the embryos. In our work we used the results of numerical simulations of the final growth of the terrestrial planets performed by Wetherill and Chambers (1997), Chambers and Wetherill (1998), and Chambers (1998). We then numerically simulated the gravitational effect of this system of embryos on a population of asteroids, using the same methodology as Petit *et al.* (1999).

In this section, we describe in detail the characteristics of the asteroid belt obtained in a series of our simulations (set A), which we consider our reference simulations in the following. In these simulations, the original system consists of 56 embryos between 0.5 and 4 AU, on circular, slightly inclined (0.1°) orbits. The other orbital elements are chosen at random. The mass of the embryos increases from the inner edge of the disk (1/60 Earth mass) to the outer edge (1/3 Earth mass), according to $M_e \propto a^3\sigma^{-3/2}$ (Lissauer 1987), where σ is the surface density of the protoplanetary disk. The total mass of embryos is $5\,M_\oplus$. The embryos are separated by a fixed number of mutual Hill radii, and the increase in mass is chosen so that the surface density σ of the system is proportional to a^{-1}. Four snapshots of the evolution of these embryos are shown in Fig. 2 (filled circles). For the first 10 My, the system consists of only the Sun and the embryos. After 10 My, Jupiter and Saturn are inserted in the simulation, with their present day masses and osculating elements.

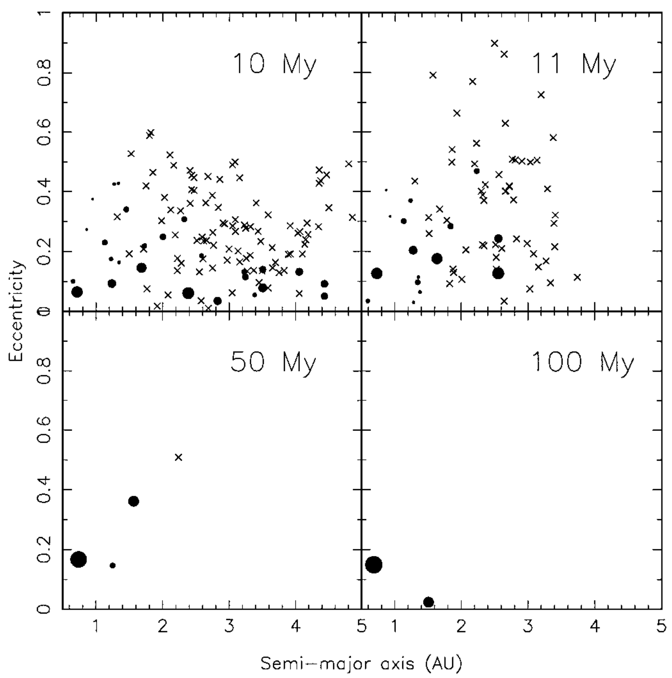

FIG. 2. Eccentricity versus semimajor axis for the massive embryos (filled circles, area proportional to mass of the embryo) and the test particles (crosses) at four different times. Jupiter is introduced in the simulation at 10 My.

In this embryo simulation, we end up with two terrestrial planets. One has a mass of 1.3 $M_\oplus$, at 0.68 AU, with eccentricity 0.15 and inclination 5°; this represents a somewhat massive and eccentric Venus. The other planet has a mass of 0.48 $M_\oplus$, at 1.5 AU, with eccentricity 0.03 and inclination 23°; this represents a very massive Mars on an inclined orbit. Only two of the embryos hit the Sun in the course of the simulation, bringing a negligible amount of mass (less than 1/27 $M_\oplus$, or less than 1/135 the original mass of embryos). Most of the mass (64%) was ejected from the system, either as unaltered embryos or as more massive embryos which had already accreted some material.

We performed several simulations of test particles in the gravitational potential of these embryos. In all the simulations in this and the following section, the test particles are started on circular planar orbits, with angles randomly distributed between 0 and 360°. The semimajor axes are uniformly distributed within a given range. Unless otherwise stated, this range is 2 to 4 AU. In the first simulation (A1), we considered 100 particles. We followed the dynamical evolution of the test particles from time zero to 10 My, when the only massive bodies present were the Sun and the embryos. The dynamical excitation gained by the test particles is moderate during this first stage and only two are lost (see Fig. 2, top-left panel, and Fig. 3 showing the number of test particles remaining in the whole system and their mean dynamical excitation versus time). When Jupiter is added at time 10 My, the excitation starts to increase much more quickly (it doubles in about 2 My) and particles begin to hit the Sun or become ejected from the system (Fig. 3).

The dramatic change in the asteroids' evolution that occurs when Jupiter is introduced into the simulation is due to the complex interplay between the gravitational scattering of the embryos and the dynamics induced by the giant planet. Indeed, the effect of Jupiter alone on an isolated body located outside mean motion resonances is to induce a secular oscillation of the eccentricity with a typically moderate amplitude; the body is not subject to radial migration. For bodies in strong mean motion resonances the eccentricity has large amplitude oscillations and may also evolve chaotically, reaching values close to unity. In this case the body may cross the orbit of Jupiter and be ejected on a hyperbolic orbit or collide with the Sun. However, the resonances cover only a small fraction of the space, so that only a small fraction of the population of bodies would have this kind of fate. If, in addition to Jupiter, the body is perturbed by one or more massive embryos, the close encounters with the latter produce a sort of random walk in semimajor axis. Consequently, the body may enter and exit the resonances with Jupiter, each passage through a resonance resulting in a large change in its eccentricity and inclination. In the presence of the massive embryos only, i.e., before Jupiter has acquired a large mass, the gravitational scattering still results in semimajor axis mobility of the body, but the absence of large and powerful jovian resonances does not allow strong pumping of e and i nor fast ejection on a hyperbolic orbit. Note that this mechanism also applies to the embryos themselves.

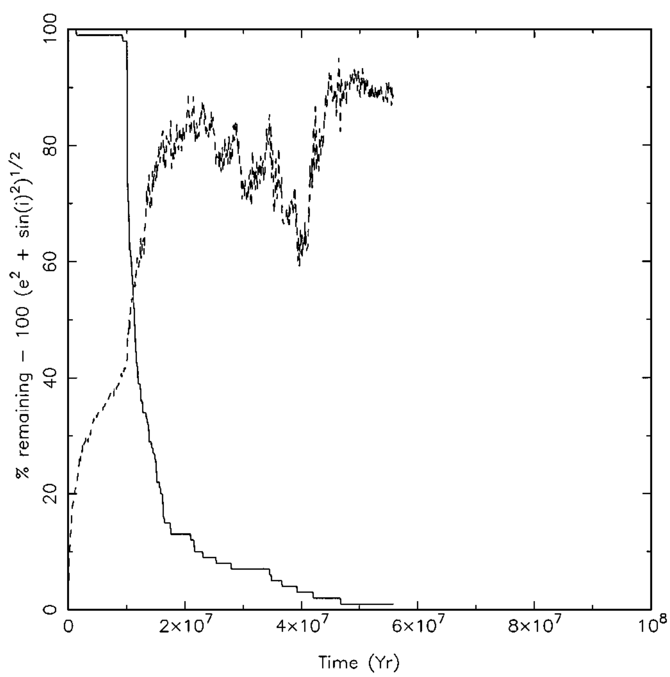

FIG. 3. Time evolution of the percentage of particles remaining in the system (solid line) and their mean dynamical excitation $\langle \sqrt{e^2 + \sin^2(i)} \rangle$ (dashed line). This corresponds to the reference simulation A1, with 100 particles on initially planar, circular orbits between 2 and 4 AU.

Given the very strong effect of Jupiter on the test particles, it seems that their evolution during the first 10 My is not important. The median lifetime of particles in simulation A1 after Jupiter is introduced is about 1.5 My. This very short time scale for the mass depletion is in good agreement with the absence of high collisional activity deduced from the existence of the basaltic crust of Vesta (Davis *et al.* 1994). No particles survived for 100 My in simulation A1; 72% of the particles were ejected from the system, 26% hit the Sun, and 2% hit a planet or an embryo. This first simulation clearly did not begin with enough particles to get statistics for the resulting asteroid belt.

For this reason, we ran a second simulation (A2) where we considered 1000 test particles. Given the results of the first simulation, we decided to start the integration at time 10 My, when Jupiter is first introduced. After $\sim$1 My of evolution, this new system is statistically indistinguishable from the previous one at time 11 My. Therefore, all other simulations were started with test particles on circular, planar orbits when Jupiter is introduced into the system. In order to save some computing time, we decided to eliminate any test particles that reached heliocentric distances less than 1.6 AU or greater than 5 AU. This was justified by the fact that particles satisfying these criteria are unstable in the real Solar System since they would have a close encounter with a terrestrial planet or Jupiter sooner or later.

At the end of the 100-My integration, only seven particles are still in the belt, all outside 2.9 AU. Six particles are in the outer part of the central belt and one is in the Hilda region. It is not possible to know the ultimate fate of the discarded particles because of our elimination criteria. However, 19% of the particles were discarded for being too close to the Sun, and the others for being too far away. In this simulation, the region below $\sim$3 AU is emptied in 21 My, and the final distribution is reached in 25 My. The relative amount of clearing in the inner part of the belt is very important and much stronger than in the real asteroid belt (see Fig. 1). Since the massive embryos spend a long time in the inner belt, a stronger depletion of that region was to be expected. The fact that the clearing was complete could be due to (1) a lack of test particles initially in the inner region below 2 AU or (2) the elimination criteria that we introduced in the simulation. It should be noted that the median lifetime dropped (from simulation A1 to A2) to 0.5 My, probably due to the different elimination criteria. However, the excitation and the rate at which the particles are removed from the asteroid belt are compatible with those of simulation A1 with no artificial elimination criteria. After about 25 My, no embryos penetrated beyond $\sim$3 AU, which explains the relative stability of the final state.

Given these remarks, we ran a third simulation (A3) with 1000 particles between 2 and 2.8 AU, starting at time 10 My. We changed the criteria for the elimination of the asteroids to a minimum heliocentric distance equal to the actual radius of the Sun and a maximum distance equal to 10 AU. The median lifetime in this simulation is 3 My, and nine particles survive the 90 My integration, five of which are still in the asteroid belt, defined as the region with $q > 1.7$ AU and $Q < 4.5$ AU: one in the inner belt, three in the central belt, and one in the outer belt. The four particles ending in the inner or central belt made a short incursion into the terrestrial planet region $q < 1.6$ AU after 1 to 5 My of integration. Hence they would have been eliminated in the previous simulation. The particles in the outer belt always stayed in the belt. Four of the particles initially in the inner belt were placed on highly eccentric and/or inclined, low semimajor axis orbits, outside the belt region. These orbits are probably unstable over the age of the Solar System, but they have a lifetime longer than 100 My. The other particles initially in the inner belt were removed from the system. The five final "asteroids" were all initially located between 2.5 and 2.8 AU. The major sink for the test particles is the Sun: 61% of them hit the Sun, 36% are ejected from the Solar System after a close encounter with Jupiter, and the other particles hit one of the planets or one of the embryos.

We also performed a fourth simulation (A4) with particles in the inner Solar System, between 1 and 2 AU. This simulation was run to see how particles far from the main-belt resonances would react and whether they could populate the inner asteroid belt (Wetherill, personal communication, 1999). Since the gravitational perturbations from Jupiter are very weakly felt below 2 AU, the only relevant perturbers are the embryos themselves. The median lifetime of these particles is 22 My, which is much longer than that for particles initially in the asteroid belt. The dynamical excitation reaches 0.9–1 and remains very high for the entire integration. There is no "stable" region at low excitation in this region since it is swept by the embryos throughout the simulation. Most of the particles are removed due to collision with the Sun. The surviving particles are found in the inner Solar System on very inclined eccentric orbits. Very few particles ever enter the belt region ($Q < 4.5$ AU and $q > 1.7$ AU), and those that do stay there only for a very short time. These particles seem to be unable to replenish the inner belt.

Combining the results from these simulations, we computed the fraction of particles in the asteroid belt, as defined above, as a function of time (solid line in Fig. 4), and also the mean dynamical excitation of the same particles (dashed line in Fig. 4). In all these simulations, the particles that remain outside the asteroid belt at the end, or at least stay there for a long time, are the ones that acquire a large inclination soon after Jupiter is inserted into the simulation. The high inclination reduces the frequency of close encounters between embryos and Jupiter and increases the relative velocities at encounter. Both effects increase the stability of these orbits. The semimajor axis, eccentricity, and inclination of the remaining particles for simulations A2, A3, and A4 (including also the surviving particles outside of the belt) are shown in Fig. 5: The A2 simulation (particles initially between 2 and 4 AU) is shown in the left panel; the A3 simulation (particles initially between 2 and 2.8 AU) is shown in the central panel; and the A4 simulation (particles initially between 1 and 2 AU) is shown in the right panel.

As mentioned earlier, gravitational interactions between the embryos and the test particles change the semimajor axes of

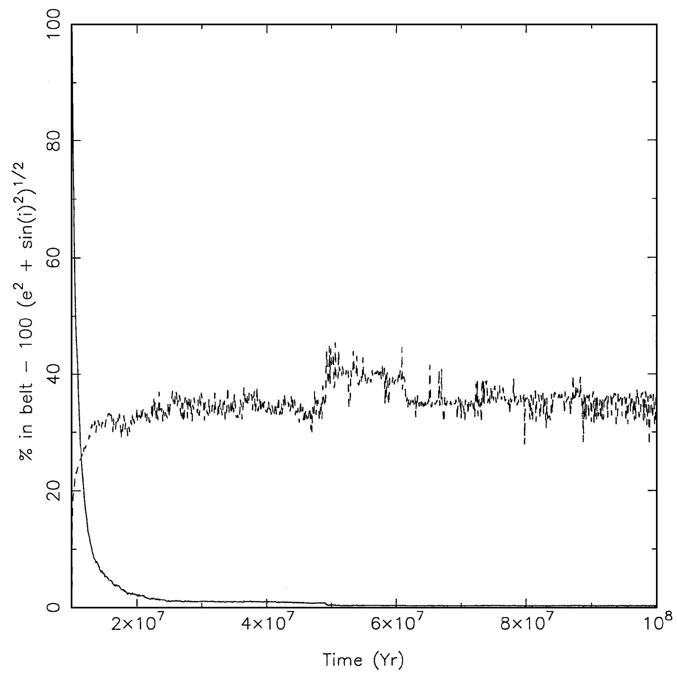

FIG. 4. Time evolution of the percentage of particles currently in the belt ($q > 1.7$ AU and $Q < 4.5$ AU; solid line) and their mean dynamical excitation (dashed line). The observed mean dynamical excitation of the real asteroids with diameters larger than 50 km is ~0.25. This plot merges all the simulations with embryo evolution corresponding to set A.

the latter, particularly during close encounters. This mechanism may explain the radial mixing of different taxonomic types of asteroids (Gradie and Tedesco 1982). We computed the radial change $|a_{final} - a_{init}|$ for all the surviving particles. In Fig. 6, we show the histogram of the radial migration for the 19 particles that survived the whole integration in all the simulations described above (dashed line). The average value is 0.30 AU and the median value is 0.23 AU. The solid line corresponds to the histogram of radial migration for the 12 particles that ended in the asteroid belt. The average is 0.24 AU and the median value is 0.2 AU.

III. RESULTS FROM OTHER SIMULATIONS

We next performed several simulations using different sets of embryos from Chambers and Wetherill (1998) and Chambers (1998). Using the MERCURY integration package (Chambers and Migliorini 1997), we also made two other embryo simulations which exhibited behaviors similar to those published by these authors. As we saw in the first series of simulations, the time spent before the appearance of Jupiter with its present-day mass is of no real importance. Hence, all the other simulations were run with Jupiter and Saturn set to their present mass at time 0. The evolution of the embryos was integrated for 100 to 400 My, depending on the simulation. Using these results, we integrated sets of test particles for 100 My, unless they all

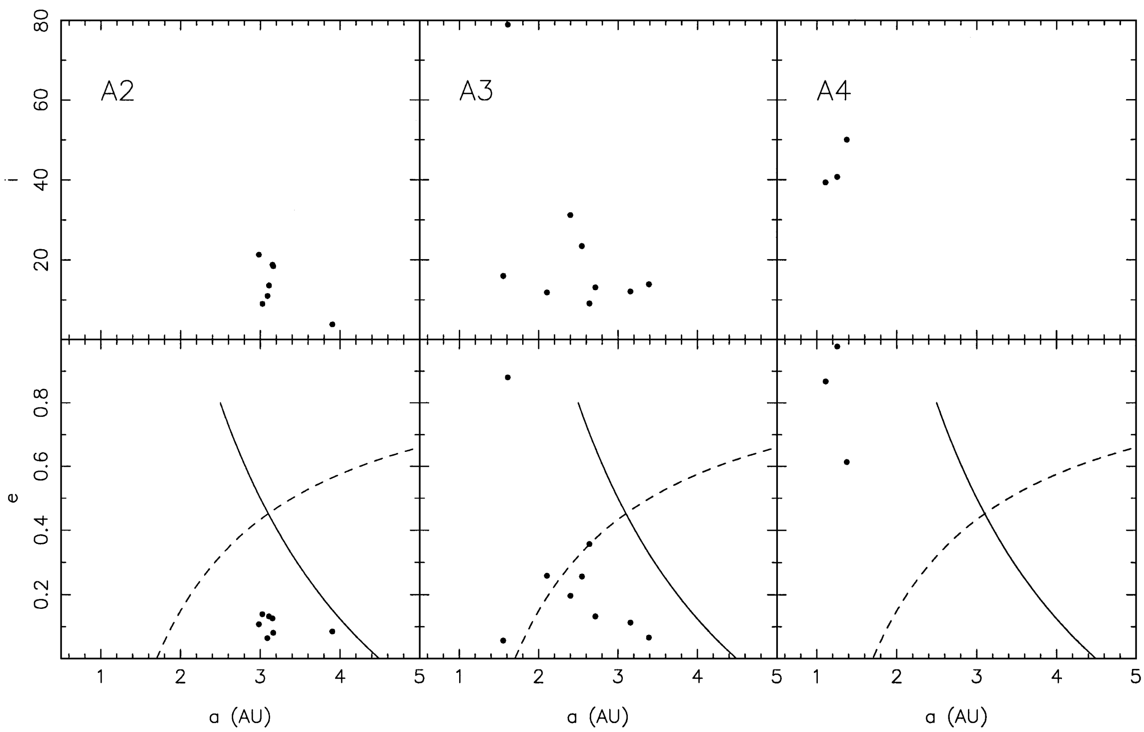

FIG. 5. Final inclination (top) and eccentricity (bottom) versus semimajor axis for the three simulations with set A where some particles survived after 100 My: simulation A2 with 1000 particles between 2 and 4 AU on the left; simulation A3 with 1000 particles between 2 and 2.8 AU in the middle; and simulation A4 with 100 particles between 1 and 2 AU on the right. Solid line: aphelion distance at 4.5 AU; dashed line: perihelion distance at 1.7 AU.

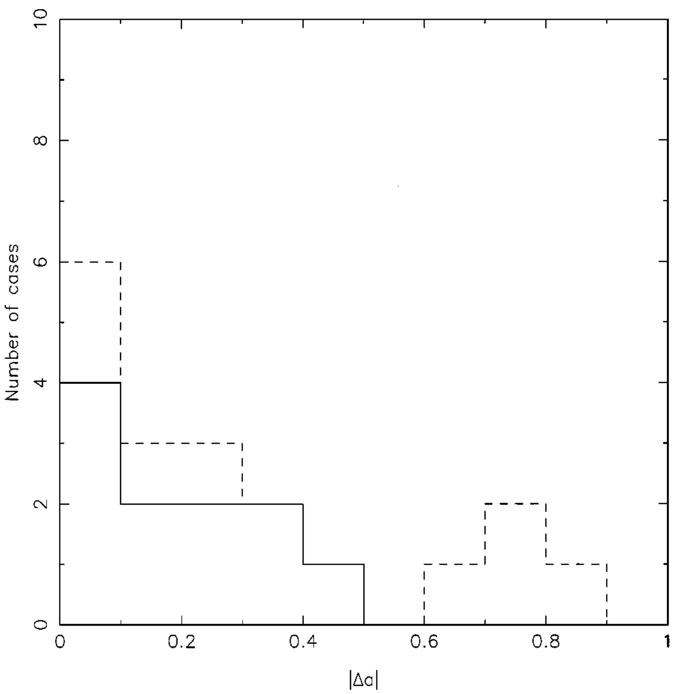

FIG. 6. Histogram of absolute value of semimajor axis changes for the particles surviving at the end of integration for integrations A1 to A4 (dashed line). Solid line: same for particles ending in the asteroid belt.

disappeared before this time (see Table II for details). Figure 7 displays the initial mass of the embryos as a function of their semimajor axis. The horizontal lines give the extent of their radial motion and the vertical dashed lines are proportional to their inclinations. Table I gives a summary of the conditions for the embryo simulations. Although there are still embryos in the asteroid belt after 100 My in most cases, they will generally (in two thirds of the cases) be eliminated at the end of terrestrial planet growth (median lifetime of 330 My; Chambers and Wetherill 2001).

In Table II, we summarize the conditions and results of the test particle simulations. We mostly report the number of particles left in the different parts of the belt and the total number left in the system. Particles which are not in the belt are in the terrestrial planet region, on very inclined and eccentric orbits. Note that the change in semimajor axis of particles staying in the belt is obviously limited by the definition of the belt (see Fig. 6). For the other surviving particles, the change is often as large as 1 AU and even reaches more than 2 AU in one case.

III.A. Fixed Surface Density

In simulations B to E, we tested the effect of the mass of the individual embryos, keeping their radial extent and their surface density profile similar to those in simulation A. See Table I for more details.

The general behavior of the test particles was the same as that in simulations A1–A4. The median lifetime is of order 1 My, and less than 1% of the particles remained in the belt after 100 My. Since some embryos were still crossing the belt after 100 My, the particles surviving in the belt may very well be on unstable orbits. The reduced clearing effect due to the smaller individual masses of the embryos in simulations C and D is compensated for by their larger number and longer residence time. The main difference between all these simulations is the fate of the lost particles (see Table II, last column).

As analogues of case A4, we ran two simulations with test particles initially in the inner Solar System: particles between 1.5 and 2 AU (simulation D2) with embryos of set D, and particles between 1 and 2 AU (simulation E2) with embryos of set E. As explained before, the only relevant perturbers in that region are the embryos. The median lifetime of these particles becomes very large, exceeding 100 My in both cases. Here again the dynamical excitation reaches 0.9–1 and remains very high for the entire integration. The fate of the particles is similar to that in simulation A4. Very few particles ever enter the belt region

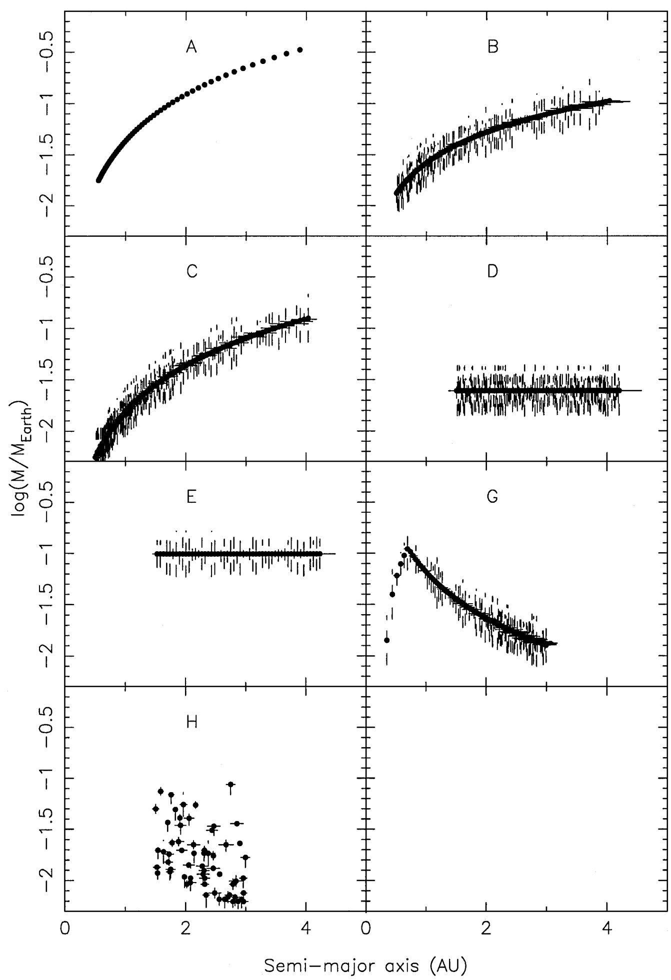

FIG. 7. Initial mass distribution of the massive embryos in the various sets of simulations. The horizontal lines show the initial radial motion of the embryos; the vertical dashed lines are proportional to the inclination.

TABLE I
Parameters for Embryo Simulations

Simulation name	N	Individual mass ($M_\oplus$)	a range (AU)	σ profile	Total mass ($M_\oplus$)	N_P (10^8 yr)	N_E (10^8 yr)	Comments
A	56	1/56–1/3	0.5–4	a^{-1}	5	2	0	
B	148	1/77–1/10	0.5–4	a^{-1}	6.6	3	3	
C	221	1/180–1/8	0.5–4	a^{-1}	6.6	3	8	
D	204	1/40	1.5–4	a^{-1}	5	1	27	
E	51	1/10	1.5–4	a^{-1}	5	1	2	
F	204	1/40	1.5–4	a^{-1}	5	0	9	Eccentric Jupiter
G	126	1/180–1/9	0.5–3	$a^{2.6}$ ($a < 0.7$) $a^{-1.5}$ ($a > 0.7$)	3.6	2	2	
H	90	1/160–1/11 random	0.5–3	a^{-1}	2.2	2	1	
I	126	1/180–1/9	0.5–3	$a^{2.6}$ ($a < 0.7$) $a^{-1.5}$ ($a > 0.7$)	3.6	2	0	Migrating Jupiter

Note. N is the number of embryos at the start of the simulation; N_P and N_E are the numbers of planets and embryos after 100 My; and σ is the initial surface density. In the simulations used here, all embryos will eventually leave the asteroid belt in less than 400 My.

($Q < 4.5$ AU and $q > 1.7$ AU), and those that do stay there only for a very short time.

III.B. *Eccentric Jupiter*

In the previous simulations, we noticed that the eccentricity of Jupiter decreased from its initial value of 0.048 (the present-day eccentricity) to almost 0, while its semimajor axis also decreased from 5.2 to 5.13 AU. Chambers and Wetherill (2001) found similar behavior, and so, like these authors, we ran a simulation (F) starting Jupiter at 5.3 AU, with eccentricity 0.1, with the same embryo distribution as in D. This increased Jupiter's efficiency in dynamically exciting and ejecting the embryos. After only 50 My, all the embryos had left the asteroid belt. At the end of the simulation, Jupiter was at 5.24 AU, with eccentricity 0.045. We integrated 200 test particles for 100 My. After 45 My, all but one of the particles had left the Solar System. The remaining particle was in the central part of the belt, in a stable region at $a = 3$ AU, $e = 0.17$, and $i = 11.4°$, which was cleared of embryos.

We also ran a simulation with test particles between 1.5 and 2 AU (F2). The results were comparable to those of A4, D2, and E2, with a median lifetime of 40 My.

TABLE II
Parameters for the Asteroid Simulations

Simulation name	N	a range (AU)	N_{left}	N_{inner}	$N_{central}$	N_{outer}	Comments
A1	100	2–4	0	0	0	0	
A2	1000	2–4	7	0	6	1	
A3	1000	2–2.8	9	1	3	1	
B	100	2.5–4	1	0	0	0	Mostly ejection
C	100	2.5–4	2	0	0	0	Mostly ejection
D	400	2–4	0	0	0	0	Mostly hit the Sun
E	400	2–4	1	0	1	0	Mostly hit the Sun
F	200	2–4	1	0	1	0	
G	100	2–4	7	0	2	5	Too many Hildas
H	200	2–4	15	0	7	8	Too many Hildas
I	100	2–4	1	0	1	0	
A4	100	1–2	3	0	0	0	Very inclined
D2	100	1.5–2	67	1	0	0	Very inclined
E2	100	1–2	81	0	0	0	Very inclined
F2	100	1.5–2	28	2	0	0	Very inclined

Note. N is the number of asteroids at the start of the simulation; N_{left} is the total number of asteroids in the system at the end after 100 My; N_{inner}, $N_{central}$, and N_{outer} are the numbers of asteroids in the inner, central, and outer belts, respectively.

III.C. *Truncated Embryo Distribution*

Next we investigated the effect of completely different embryo mass distributions. In simulations G and H, we truncated the distribution of embryos at 3 AU. This situation could have occurred if the forming Jupiter had accreted all the massive embryos in the outer belt or aborted their runaway growth. To speed up the integration of the test particles, we eliminated particles if their heliocentric distance became less than 1.6 AU or greater than 5 AU. In simulation H, we retained embryos only if they were at a heliocentric distance larger than 1.5 AU (hence the distribution plotted in Fig. 7). The final distributions of the test particles in both cases were very similar. Figure 8 shows the eccentricity and inclination versus the semimajor axis of the surviving particles for both simulations. All the particles are beyond 2.9 AU, and almost half of them are in the Hilda region. Clearly, there are too many Hildas, and this is a direct consequence of the lack of embryos in the outer belt.

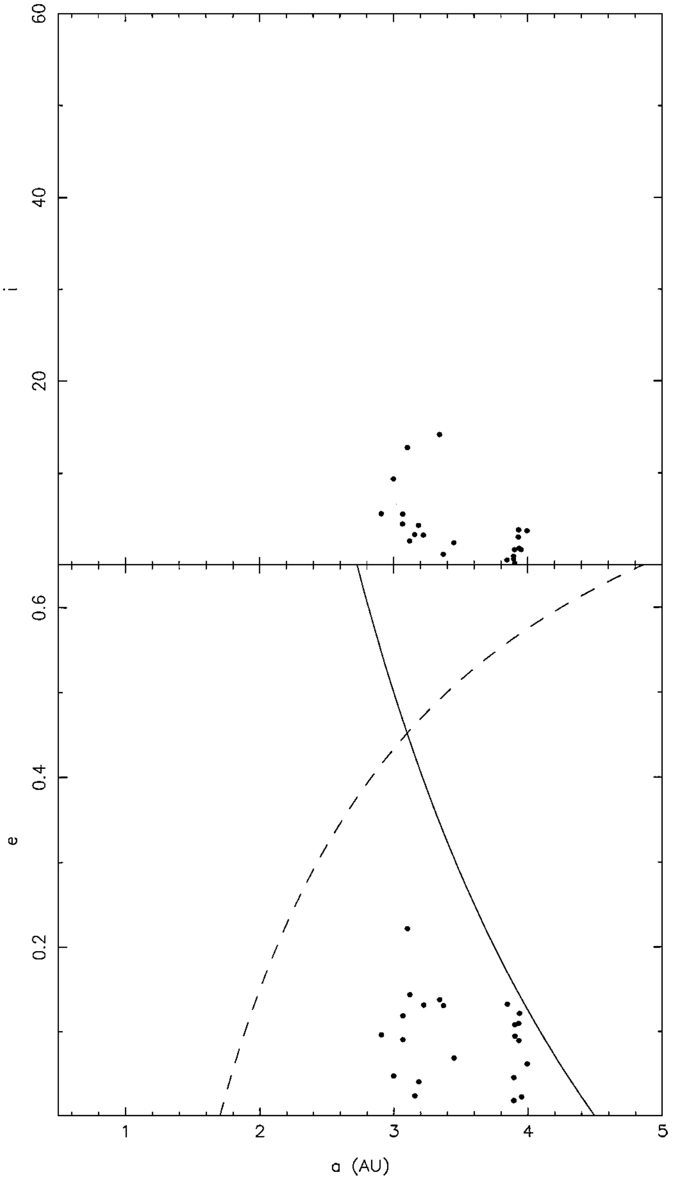

FIG. 8. Final inclination (top) and eccentricity (bottom) versus semimajor axis for simulations G and H combined. Solid line: aphelion distance at 4.5 AU; dashed line: perihelion distance at 1.7 AU.

III.D. *Migrating Jupiter*

Finally, we investigated briefly, in simulation I, the effect of a noticeable migration of Jupiter from 6.4 to 5.2 AU. We force the inward migration of Jupiter by adding an exponential decay with a timescale of 10 My to its natural motion. In the same time, Saturn migrates freely outward from 9.5 to 10.3 AU. The initial distribution of embryos is identical to that of simulation G. The migration of Jupiter's mean motion and secular resonances during the first 20 My increases its efficiency at exciting and ejecting the embryos. However, at the very beginning, the resonances were further out than in the present Solar System, and the test particles in the belt were not subject to Jupiter's excitation. Hence the median dynamical lifetime of test particles is longer than those in the other simulations, at about 10 My. However, after this inital delay, the excitation is as large as in the previous cases, and only 1 particle of 100 integrated, is left after 100 My, in the central belt, on an orbit with inclination oscillating between 30 and 40°, and eccentricity oscillating between 0.1 and 0.6. The high inclination is gained early in the evolution, between 3 and 10 My, due to the sweeping of a secular resonance. In contrast to simulation G, no particle is left in the Hilda region. Hence, the migration of Jupiter may compensate for the lack of embryos in the outer belt.

IV. DISCUSSION

In all the previous simulations, we see clearly that the presence of large embryos in the inner Solar System for about 100 to 200 My after Jupiter has reached its present-day mass provides an efficient mechanism for depleting the asteroid belt of most of its primordial mass and for dynamically exciting the remaining small bodies. This result is robust with respect to changes in the initial distribution of massive embryos. Our model seems to reproduce globally the main features of the asteroid belt, dynamical excitation, mass depletion, and mixing of taxonomic types, with values that are in quantitative agreement with observed values. The radial mixing is substantial in our model, typically larger than a few tenths of an AU, even as large as 1 AU or more in some cases. To our knowledge, this is the only model which generates a wide distribution in eccentricity and inclination of asteroid orbits, together with substantial radial mixing. The effects described in this paper are inescapable if we believe that terrestrial planets were formed by collisional accretion of embryos from less than 0.5 AU up to about 4 AU. Currently, this hypothesis is among those capable of building the terrestrial planets, with the correct timescale. In addition, Morbidelli *et al.* (2000a) showed that this model is compatible with the delivery of water to Earth, from the point of view of mass and also of isotopic composition.

Our simulations show also that embryos must have existed outside 3 AU if this model is correct. Otherwise, we get too many asteroids in the outer part of the belt, in particular too many Hildas. Hence the forming Jupiter should not have aborted the runaway growth of large embryos in the outer belt nor accreted them too early while still growing. The only way to circumvent this constraint is to have Jupiter migrating from further than 6 AU inward to its current location. In this case, even without embryos in the outer belt, the asteroids in that region are ejected. However, it is difficult to imagine that if Jupiter formed that far out it could prevent the formation of embryos in the asteroid belt zone.

The major problem of our model is the almost complete depletion of the inner belt. The observed asteroid belt is actually more depleted in the inner part than in the central or outer parts. But the depletion we obtain for the inner belt seems to be too strong. This feature puts strong constraints on the details of terrestrial planet formation models.

There are several reasons for this severe depletion of the inner belt, most of them related to the fact that we do not reproduce exactly the actual terrestrial planets. First, when a planet is created on an orbit close to that of Mars, it is generally too big. Hence the region which is dynamically perturbed by this planet extends further than 1.7 AU as in our Solar System. Second, in about 30% of our planetary accretion simulations, there were planets in the inner belt at the end of the evolution. This obviously prevents the existence of asteroids in that region. Third, the planets tend to have a rather large eccentricity, hence destabilizing the inner Solar System further out than in the real world. The fourth reason seems to be more of a problem. In all our embryo simulations, even in the best ones (as far as reproducing the terrestrial planets is concerned), the embryos tend to stay too long in the inner belt. The ejection of the embryos proceeds from the outside in. The embryos in the inner belt are ejected on a timescale of a few times 10 My, while the excitation and depletion timescale of the test particles is on the order of a few million years.

Clearly more studies are needed, for example, on the effects of partial accretion—i.e., some sizable fragments are generated from primordial impacts, generating “primordial asteroids” in the inner belt—the effects of resonance sweeping due to nebula dissipation and giant planet migration, and finally collective effects. These processes may help reduce the mass of Mars analogues, the eccentricity of the terrestrial planets by dynamical friction (Agnor *et al.* 1999), and the lifetime of embryos in the inner belt.

In all our simulations, we found that some test particles moved to small semimajor axis, large eccentricity, and large inclination orbits that survived much longer than other orbits in the inner Solar System and most of the orbits in the asteroid belt region. These long-lived orbits are populated by particles initially in the inner Solar System or in the asteroid belt. In the real Solar System, the total mass of such objects could have been larger than the current mass of the asteroid belt. In our simulations, a few percent of the particles end up on these long-lived orbits, equivalent to several times the mass of the present asteroid belt. These orbits are unstable on a long timescale and represent a potential source of impactors for the Late Heavy Bombardment, as shown by Morbidelli *et al.* (2000b).

Finally, another implication of our model has been proposed by Asphaug *et al.* (2000): In our model, the asteroids have frequent close encounters with massive embryos. Up to 10% of the asteroids enter the Roche zone of an embryo at least once, and a few percent come so close that the tidal forces would strip away the mantle of a differentiated asteroid, hence exposing the metallic core. This could explain the existence of M-type asteroids. A more detailed study of this possibility is under way.

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