Planetary Embryos Never Formed in the Kuiper Belt

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We study the orbital evolutions of various systems of planetary embryos in the transneptunian region, undergoing mutual scattering and perturbations from the giant planets. We show that about 15–20% of the original embryos should survive in the transneptunian region at the current epoch. The orbital dispersion of the surviving embryos depends on their individual mass, so that only lunar mass embryos could survive with semimajor axis smaller than 50 AU. In all cases, we show by a Monte Carlo model that at least one of the surviving embryos should have already been discovered by one of the most effective Kuiper-belt surveys. This implies that planetary embryos did not form in the transneptunian region (or have been removed by some external and unknown mechanism). Therefore, we conclude that the Kuiper belt was not excited by resident planetary embryos, unlike the asteroid belt. We also compute with the Monte Carlo model that a significant number (order 10) of Pluto-size bodies could exist only on very eccentric and long-periodic orbits, typical of the scattered disk, while the existence of about 30 bodies brighter than absolute magnitude 4 in the classical belt is compatible with the discovery of Varuna by the Spacewatch survey.   © 2002 Elsevier Science (USA)

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1. INTRODUCTION

It is well evident now, from the orbital distribution of multi-opposition objects, that the Kuiper belt is strongly dynamically excited. That is, the eccentricities and the inclinations are typically much larger than those expected for a protoplanetary disk of planetesimals. This is true not only for the *Plutinos* (bodies currently in the 2 : 3 resonance with Neptune) but also for the so-called *classical belt* objects (bodies with semimajor axis between 40 and 48 AU and not in any notable mean motion resonance with a planet). In addition, the total mass of the Kuiper-belt in the 30–50 AU range (Trujillo *et al.* 2001, Gladman *et al.* 2001) seems to be two to three orders of magnitude smaller than the

primordial mass, the latter being deduced by extrapolation of the surface density of solid materials incorporated in the giant planets (Weissman and Levison 1997) and by accretion models for Kuiper-belt objects (Stern 1996, Kenyon and Luu 1998, 1999).

Several mechanisms have been proposed so far to explain the orbital excitation and the mass depletion—including collisional grinding (Stern and Colwell 1997), mean motion resonance sweeping (Malhotra 1993, 1995, Hahn and Malhotra 1999), secular resonance sweeping (Nagasawa and Ida 2000), Neptune-scattered planetesimals (Morbidelli and Valsecchi 1997, Petit *et al.* 1999), a temporarily Kuiper-belt-crossing Neptune (Thommes *et al.* 1999) and a passing star (Ida *et al.* 2000)—but none of them seems to be completely satisfactory.

The massive Neptune-scattered planetesimal model hypothesizes the existence of a terrestrial planet-mass body, scattered by Neptune onto an eccentric orbit that crosses the Kuiper belt up to large heliocentric distances for some 10^8 years. This model is appealing because it qualitatively explains in a unitary scenario both the strong mass depletion of the Kuiper belt (by emplacement of most of the primitive Kuiper-belt bodies onto Neptune-crossing orbit) and the excitation of the eccentricities and inclinations of the remaining bodies (see Fig. 3 of Petit *et al.* 1999). However, an important qualitative problem with this scenario is that the fraction of the initial Kuiper-belt population that survives at the end of the excitation phase (when the Neptune-scattered planetesimal is dynamically removed) is a monotonically increasing function of the semimajor axis. This is in evident contrast with the existence of many Plutinos at 39–40 AU (which constitute 4% of the entire Kuiper-belt population up to 50 AU, according to the latest estimates by Trujillo *et al.* 2001), and with the apparent paucity of bodies beyond 50 AU (Trujillo and Brown 2001). Interestingly, the Petit *et al.* (1999) paper shows that the same problem exists in the analogue scenario of a massive Jupiter-scattered planetesimal exciting the asteroid belt: a very strong excitation and depletion occurs close to Jupiter, where no Hildas (asteroids in the 3 : 2

resonance with Jupiter) can survive; conversely, the portion of the asteroid belt far from Jupiter stays essentially undepleted and unexcited. This is due to the fact that a Jupiter- or Neptune-scattered planetesimal must pass close to the planet's orbit at every revolution, while it transits through the regions far from the planet only during the high-eccentricity phases of its orbital evolution.

For the asteroid belt, a plausible solution of the problem of a uniform excitation invokes the primordial presence, throughout the belt and the inner Solar System, of many planetary embryos with lunar to martian masses, formed by runaway growth. Simulations show that in 2/3 of the cases all the embryos leave the asteroid belt due to their mutual interactions and jovian perturbations (Chambers and Wetherill 2001), while in the inner Solar System the embryos accrete each other, forming a few terrestrial planets (Chambers and Wetherill 1998, Agnor *et al.* 1999, Chambers 2001). Petit *et al.* (2001) have shown that, before leaving the asteroid belt, the embryos eject more than 99% of the asteroids into the planet-crossing region, leaving the remaining ones with eccentricity and inclination distributions resembling those observed in the current asteroid belt. Because the embryos closest to Jupiter are those that are eliminated first, the excitation and depletion of the asteroid population in the outer belt are comparable to those in the inner belt, where the embryos reside over much longer time scales. As a consequence, at the end of the excitation phase, a nonnegligible fraction of the surviving asteroids are in the 3 : 2 resonance with Jupiter, consistent with the existence of the Hildas.

By analogy with this successful scenario, it is tempting to conjecture that planetary embryos also formed in the Kuiper belt and—before leaving the belt due to their mutual interactions and Neptune perturbations—depleted and excited the population of the small Kuiper-belt objects, more or less uniformly with respect to semimajor axis. The goal of this paper is to simulate the orbital evolution of the putative Kuiper-belt embryos, for different initial distributions. In Section 2, we describe the initial conditions and the orbital evolutions and conclude that, unlike the asteroid belt case, some 15–20% of the embryos would survive for the age of the Solar System. In Section 3, we compute the probability that the surviving embryos have all escaped detection until now. The implications of the results are discussed in Section 4.

2. ORBITAL EVOLUTION OF PLANETARY EMBRYOS IN THE KUIPER BELT

The simulation of formation of planetary embryos by runaway and oligarchic growth (Kokubo and Ida 1998) suggests that embryos typically form in an ordered chain in heliocentric distance, characterized by a constant separation in units of mutual Hill radii. Because the mutual Hill radius grows linearly with the heliocentric distance r, and the primordial surface density of solid material presumably decreases as $1/r^2$ (Pollack *et al.* 1996), it is reasonable to assume in first approximation that the mass of the individual embryos was independent of their loca-

TABLE I

Simulation	N	M	a-range	M_{tot}	Sc. fact.	F_{surv}
1	50	0.750	24.6–43.5	37.7	1.424	0.18
2	50	0.440	23.6–37.8	22.0	1.480	0.12
3	70	0.160	28.5–45.6	11.0	1.228	0.17
4	150	0.100	25.6–39.8	15.5	1.369	0.13
5	150	0.014	33.0–52.2	2.1	1.059	0.18
6	539	0.015–0.96	15.3–49.2	27.0	1.292	0.25

Note. Summary of the numerical simulations. The first entry reports the simulation number. The second column gives the initial number of embryos, whose individual mean mass is reported in the third column, in Earth mass units. The fourth column gives the initial semimajor axis range of the embryo population, in AU. The fifth column gives the total mass of the embryo population, in Earth mass units. The sixth column reports the scaling factor, relating AU to integration length units (see text). The last column shows what fraction of the embryo population survives at the end of the integration. For simulation #6, which is distinct from the previous ones because it is characterized by a mass distribution of embryos and Neptune ends its migration at approximately 30 AU, F_{surv} is computed with respect to the embryo population in the two bins of largest mass, and the scaling factor indicates the difference between the final and initial values of Neptune's semimajor axis.

tion. In simulations #1 to #5, we therefore consider systems of roughly equal mass embryos, separated by 1 mutual Hill radius (0.5 mutual Hill radii in the case of simulation #4). The mass of the embryos that could form in the Kuiper-belt (dependent on the primordial surface density and on the efficiency of the runaway growth process) is largely unknown, so that it is the major parameter that characterizes our different sets of initial conditions. In simulations #1 to #5, we consider embryos of 0.72, 0.44, 0.16, 0.10, and 0.015 $M_\oplus$, respectively (simulation #6 is discussed below). We believe this selection of embryos will allow us to explore a suitably wide range of possibilities. The total number of embryos, their range in a, and their total mass are listed in Table I. The initial eccentricities and inclinations of the embryos have been randomly assumed in the interval 0–10^{-3}.

The simulations have been done using the *Mercury* integrator (Chambers 1999), which behaves symplectically even during close encounters among massive bodies. In addition to the embryos, the integrations included the presence of the four giant planets, initially on their current orbits, and covered 4.5 Gyr. The integration time step (away from close encounters) was 1 year. During the integrations, Neptune migrated outwards and ended significantly beyond 30 AU. This makes the comparison between the final state of the simulated system and the current Kuiper belt difficult. However, it is well known that the dynamical evolution is independent of an arbitrary rescaling of the unit of length, provided that the unit of time is also properly rescaled. Thus, in each simulation we scale the semimajor axis so that Neptune ends its evolution at 30 AU. This implicitly assumes that the initial conditions have been given in integration length units (ILU)—related to the usual AU by the relationship 1 ILU = $30/a_{fin}$ AU, where a_{fin} is the final semimajor axis of Neptune in ILU— and that the integrations covered 4.5×10^9 integration time units (ITU), with 1 ITU = $(30/a_{fin})^{3/2}$ years.

The scaling factor $30/a_{fin}$ for simulations #1 to #5 is reported in Table I. All the results shown hereafter will be expressed in AU and years, not in integration units. Of course, with this trick, the final semimajor axis of Neptune is correct, but those of the other giant planets are not. However, we believe this is only a minor problem for the following reasons. First, the evolution of the embryos is strongly dominated by their mutual interactions and by Neptune perturbations, while it is only moderately affected by the direct perturbations exerted by the other planets. Second, the secular resonances, whose locations are misplaced as a result of the incorrect relative positions of the planets, play only a minor role in sculpting the Kuiper belt. They are indeed quite weak, and the random movements in semimajor axis of planets and embryos do not allow the latter to reside in secular resonance long enough to suffer significant modifications of their orbits; in all integrations, we have not observed any embryo evolution that might be reconduced to the action of a specific secular resonance. The fact (illustrated below) that the result of simulation #5 (where the planets do not undergo significant migration) is similar to those of the other simulations will further support our claim that the positions of Jupiter, Saturn, and Uranus are not of primary importance.

Figure 1 shows four snapshots of the orbital distribution of the embryos in simulation #3. Each embryo is represented by a
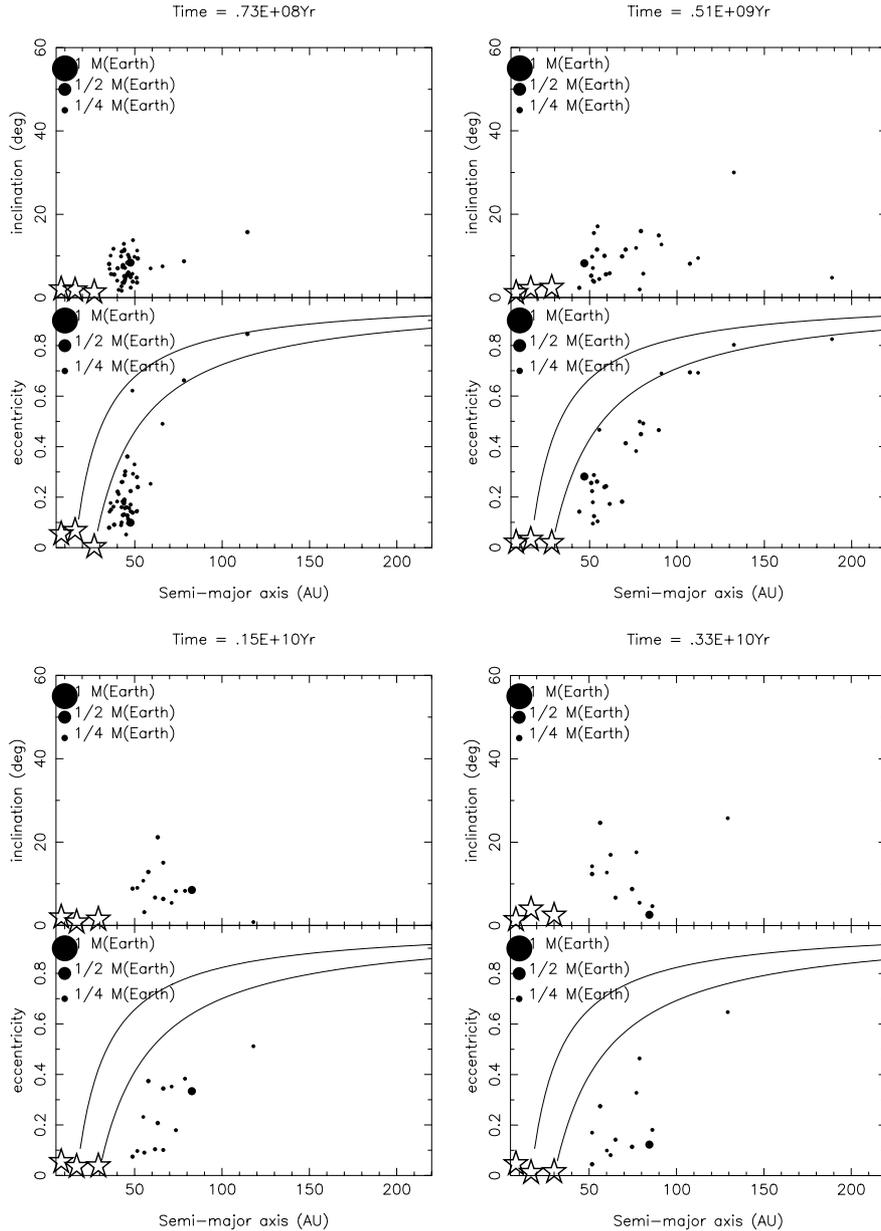

FIG. 1. Snapshots of the evolution of the embryos in simulation #3, at the times reported on top of each panel. The embryos are represented by filled dots, whose size is linearly proportional to their mass. The stars denote the orbits of Saturn, Uranus, and Neptune. The solid curves show the equations $q = a_U$ and $q = a_N$, where q is the perihelion distance and a_U and a_N are the semimajor axes of Uranus and Neptune, respectively.

dot whose size is linearly proportional to its mass. The system of embryos, which is initially extremely dynamically cold, excites very rapidly. Within 73 Myr, 33% of the initial embryos have become planet crossers and have been eliminated by the subsequent dynamics. Most of the surviving embryos still have semimajor axes smaller than 50 AU, but they have acquired eccentricities up to 0.4 and inclinations up to 15 deg. After half a billion years, only 37% of the embryos survive, and they are now much more spread in semimajor axis. Only a few embryos have $a < 50$ AU. The inclination excitation reaches 20 deg. At 1.5 Gyr, the fraction of surviving embryos has decreased to 20%, and the survivors are now all quite far from the Neptune crossing limit. Then, until the end of the integration at 3.3 Gyr, not much happens. Only two embryos are lost during this period, and the overall orbital distribution does not significantly change. This is because the embryos are spread enough in orbital space that their mutual encounters become rare and ineffective. Therefore, although the individual evolutions of the embryos are chaotic, the system of embryos as a whole reaches a sort of "stable" configuration. Notice that during the entire evolution only one embryo has grown in mass. In fact, only one binary collision between embryos has been recorded, immediately after the beginning of the integration, when the system is still dynamically very cold. This shows the extreme difficulty of accreting large bodies in these distant regions of the Solar System, as already discussed by Levison and Stewart (2001). Two embryos hit Saturn and one hits Uranus. All the other removed embryos have been transported by planetary encounters beyond 1000 AU, where the integration of their evolution has been stopped.

All other simulations, starting with bigger or smaller embryos, show essentially similar evolutions, and Fig. 2 shows the final orbital distributions. As one can see, several embryos remain at the end of each simulation. The more massive the embryos are, the more dispersed is the final orbital distribution of the survivors. In particular, simulation #5, with lunar mass embryos, is the only one that leaves embryos in the region with $a < 50$ AU.

As shown in Fig. 4, the relative decay of the embryo population is essentially the same in all simulations, with about 15% of the embryos surviving at the end. It may be surprising that the populations of the most massive embryos do not decay faster than those of the less massive ones, but this happens because the most massive embryos are capable of achieving a larger dispersion in orbital space.

This result leads one to wonder what would happen if the embryos, instead of all having the same mass, had a size distribution. Therefore, we ran a sixth simulation with 539 embryos, with masses of 0.015 (272 embryos), 0.03 (136 embryos), 0.06 (68 embryos), 0.12 (34 embryos), 0.24 (17 embryos), 0.48 (8 embryos), and 0.96 $M_\oplus$ (4 embryos). The total mass was 27 $M_\oplus$, and the embryos of each mass bin were uniformly distributed between 15.3 and 49.2 AU. Moreover, we assumed initial semimajor axes of Jupiter, Saturn, Uranus, and Neptune equal, respectively, to 5.88, 7.87, 13.20, and 23.22 AU, so that the final value of Neptune's semimajor axis was about right

(29.96 AU). No rescaling of the units of length or time was therefore required. Snapshots of the evolution of this simulation are shown in Fig. 3. With respect to the other simulations discussed above, we observe that dynamical friction tends to damp the eccentricities and inclinations of the most massive embryos, while the smallest embryos suffer a stronger dynamical excitation. As a consequence, almost all the small embryos were eliminated from the system before the end of the simulation, while two of the most massive embryos could survive with eccentricity and semimajor axis smaller than in simulation #1. In total, only six embryos remained—two of the smallest, two of the largest, one of mass 0.06 $M_\oplus$, and one which resulted from the accretion of a 0.24-$M_\oplus$ embryo by a 0.48-$M_\oplus$ one. Thus, 25% of embryos of the two largest bins survive over the age of the Solar System, a result similar to those of simulations #1 to #5 (see Fig. 4).

We are therefore confronted with a generic result: *if the Kuiper belt had been excited by the presence of a system of planetary embryos, a significant fraction (15–20%) of the original embryos should still be present at the current epoch, although possibly in the distant space.* This result is dramatically different from that in the asteroid belt case, where—as discussed in the introduction—all embryos leave the belt in 2/3 of the simulations. The reason for this difference is that the asteroid belt is bracketed by the terrestrial planets and Jupiter. The asteroid belt embryos that go outwards are ejected by Jupiter on hyperbolic orbit, and the embryos that go inwards are rapidly removed by accretion in the growing terrestrial planets or collisions with the Sun. Conversely, the Kuiper belt is delimited on the inner side by Neptune but has an infinite extension on the outer side. The embryos that migrate outwards become sufficiently isolated to be able to survive over the age of the Solar System.

3. PLANETARY EMBRYOS AND KUIPER-BELT SURVEYS

We now investigate whether the existence of planetary embryos in the current Kuiper belt, as given by the end-states of our simulations, is compatible with the observational constraint that none of these massive objects has been discovered so far.

For this purpose, we consider the Kuiper-belt surveys which have been the most effective in terms of sky coverage and/or limiting magnitude, reported in Sheppard *et al.* (2000) and listed in Table II. For simplicity, we assume that each survey covered a band, symmetrically placed around the ecliptic, spanning 320° in ecliptic longitude (i.e., leaving ±10° around the galactic plane), with the exception of the Sheppard *et al.* (2000) survey which covered approximately 45°. From this and the total sky area observed, we compute an effective maximal ecliptic latitude for discovery, listed in Table II.

For each simulation, we take the list of the surviving embryos. The mass of each embryo is converted into a diameter D, assuming a density of 2 g/cm^3, characteristic of Pluto. The albedo p is assumed to be equal to 0.04, suitable for Kuiper-belt objects
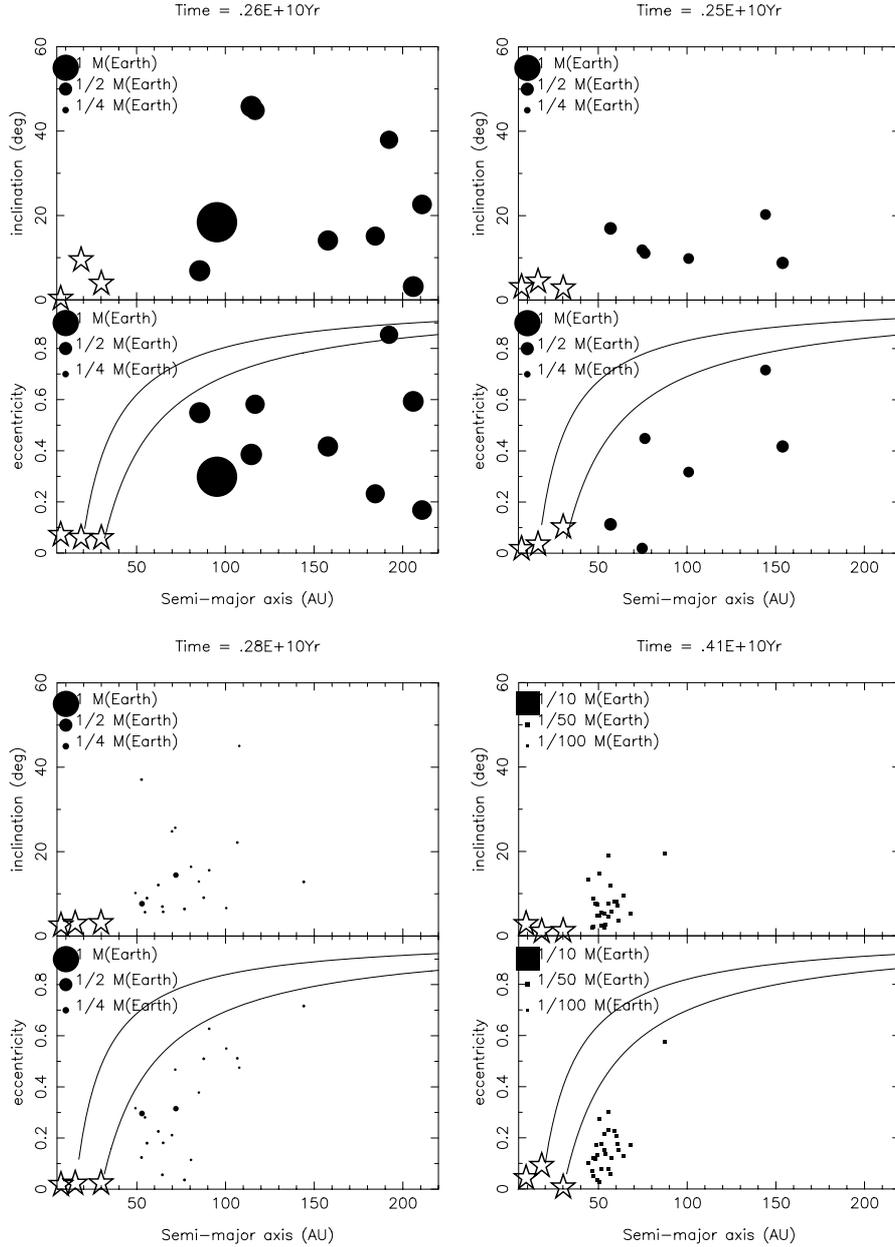
FIG. 2. Orbital distribution of the embryos surviving at the end of simulations #1 (top left), #2 (top right), #4 (bottom left), and #5 (bottom right). The representation is similar to that in Fig. 1. Notice that for simulation #5, the mass scale has been modified, and the shape of the symbols denoting the embryos has been changed to avoid confusion.

(KBOs), although we should keep in mind that the higher albedo of Pluto suggests that planetary embryos might be more reflective and therefore easier to discover. For each embryo, we take the values of a, e, i recorded at the end of the integration and generate at random a large number of values of the angles M, ω, and Ω (mean anomaly, perihelion argument, and longitude of ascending node). For each set of orbital elements, we compute the ecliptic latitude and longitude and the geocentric distance Δ (assuming that the observation is done at opposition). The latter allows us to compute the apparent magnitude from the

formula

$$m_R = 24.2 + 2.5 \log_{10}\left[\left(\frac{p}{0.04}\right)^{-1}\left(\frac{D}{100\,\text{km}}\right)^{-2}\left(\frac{\Delta}{35\,\text{AU}}\right)^4\right].$$

We consider that a discovery occurs if the ecliptic latitude and longitude of the embryo fall in the observed band of the sky, and if m_R is brighter than the limiting magnitude of the survey. Then, for a given embryo (labeled by index k) and a given survey (labeled by index j), the probability of discovery $p_{k,j}$ is computed
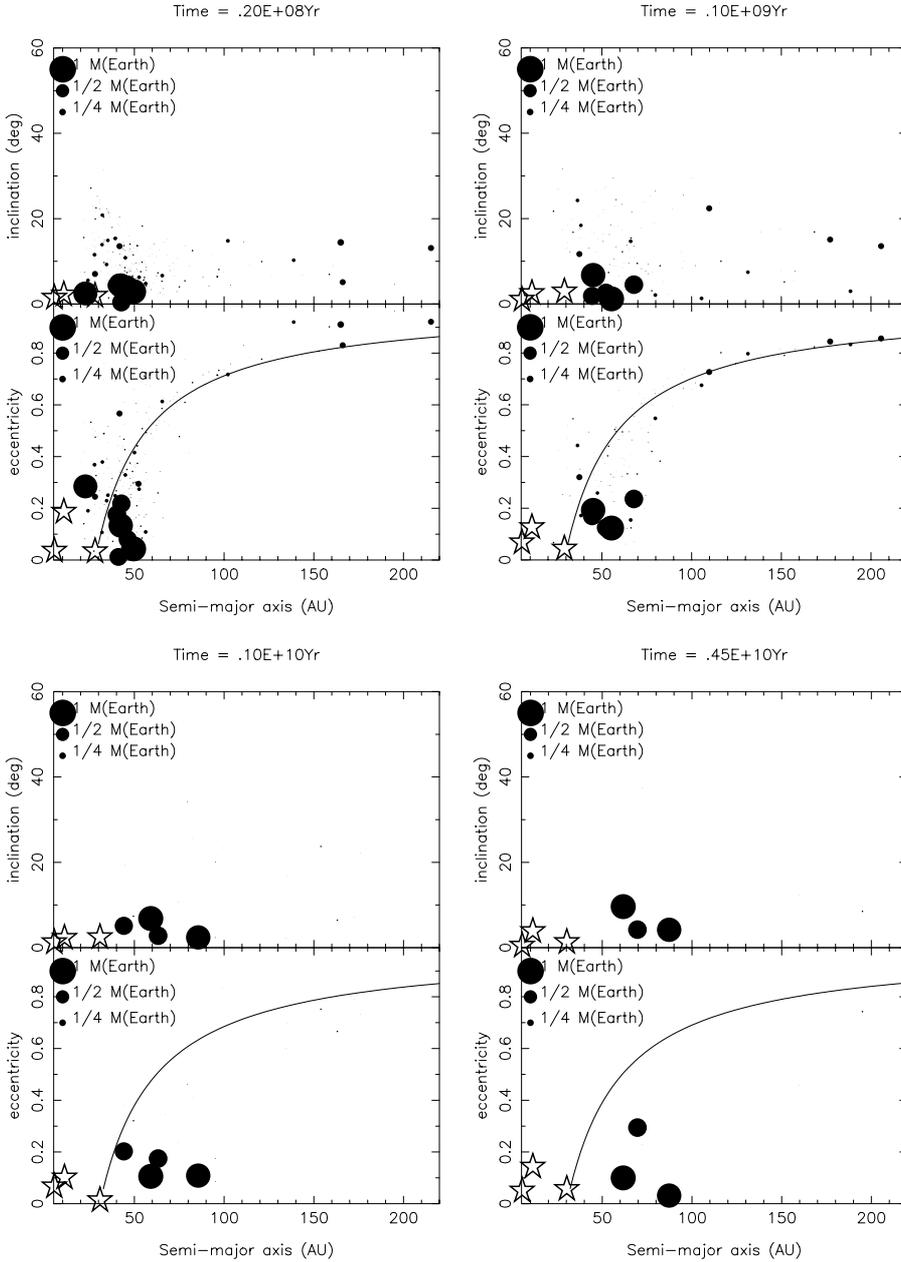
Time = .20E+08Yr

Time = .10E+09Yr

Time = .10E+10Yr

Time = .45E+10Yr

FIG. 3. The same as Fig. 1, but for simulation #6.

as the number of randomly generated values of M, ω, Ω that correspond to a discovery, relative to the total number of generated values, as standard in Monte Carlo techniques. The probability that at least one embryo is discovered by the survey j is then

$$P_j = 1 - \prod_{k=1}^{N}(1 - p_{k,j}),$$

where N is the total number of embryos.

The probabilities P_j are listed in Table II for each of our simulation end-states. The probability that at least one embryo

is detected by at least one survey is

$$P = 1 - \prod_{j=1}^{S}(1 - P_j),$$

where S is the total number of surveys, reported in the last row of Table II. As one can see, this probability is extremely high for each simulation. The probability P is higher for the end-states of the simulations that involve the less massive embryos. This is because the very massive embryos typically end on orbits with a large semimajor axis and a very large inclination, while the less
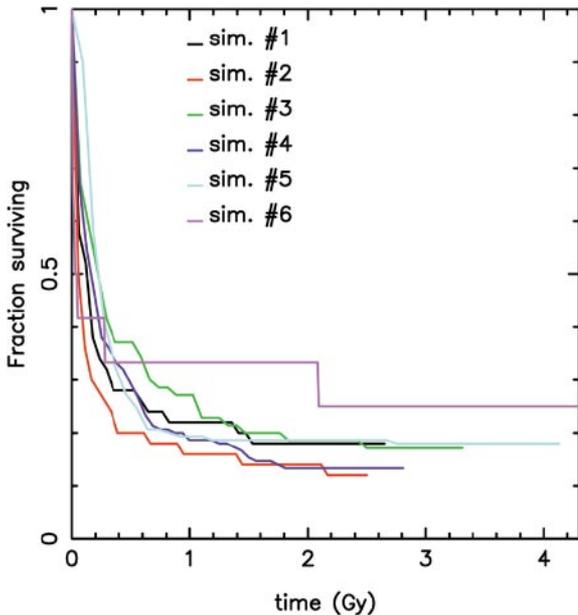
FIG. 4. The relative decay of the embryo populations, in the six simulations. For simulation #6, characterized by a mass distribution of embryos, we show the decay of the embryo population in the two bins of largest mass.

massive embryos (martian mass or lunar mass) survive in larger number in the inner Kuiper-belt and on less excited orbits. Notice that the parameters in our Monte Carlo simulations have been chosen such that P is a sort of lower bound of the real detection probability: the albedo of the embryos has been set equal to 0.04 and the limiting magnitude of the Kowal (1989) survey (which is controversial) has been pessimistically set equal to

TABLE II

Survey	m_{lim}	Surf.	ecl. lat. lim.	#1	#2	#3	#4	#5	#6
Tomb.1	16.8	1530	2.4	0.15	0.25	0.55	0.49	0.37	0.35
Tomb.2	15.5	19500	32.1	0.22	0.58	0.52	0.68	0.00	0.54
Tomb.3	15.0	25500	44.1	0.20	0.30	0.11	0.44	0.00	0.24
Kowal	17.5	6400	10.1	0.59	0.82	1.00	1.00	1.00	1.00
Shepp.	18.5	1428	16.1	0.26	0.42	0.73	0.81	0.95	0.34
SW.	21.0	1000	1.6	0.50	0.43	0.90	0.78	1.00	0.39
Total				0.92	0.99	1.00	1.00	1.00	1.00

Note. The probability that at least one embryo, among those surviving at the end of each simulation, is discovered by the major Kuiper-belt surveys. The first column indicates the author of the survey: Tomb.1, Tomb.2, and Tomb.3 refer to Tombaugh's surveys (Tombaugh 1961); Shepp. means Sheppard *et al.* (2000), and SW. denotes the Spacewatch survey. The second column reports the limiting magnitude of the survey; the limiting magnitude of Kowal's (1989) survey is controversial, and we use its most conservative value. The third column gives the total sky area covered by the survey, in square degrees, and the fourth column reports the effective ecliptic latitude limit for discovery, computed as explained in the text. The remaining columns show, for each simulation, the probability P_j that at least one embryo is discovered by the survey j. The last row reports the cumulative probability, over all the considered surveys, that at least one embryo is discovered.

magnitude 17.5. Had we attributed to the embryos the albedo of Pluto or set a limiting magnitude of 18.5 for the Kowal (1989) survey, the probability P would have been equal to 1 for all simulations.

4. IMPLICATIONS AND DISCUSSION

We have shown that, if the Kuiper belt had been excited by the primordial presence of a system of planetary embryos, about 15–20% of the original embryos would still survive in the transneptunian region, and at least one of them should have been discovered already.

This very likely implies that a system of numerous planetary embryos, even of lunar mass, never formed in the transneptunian region. This conclusion on the nonexistence of planetary embryos is consistent with the result that, according to N-body simulations (see Section 2), the accretion of massive bodies in the outer Solar System is extremely difficult. This point has been discussed often in the literature and was recently revisited by Levison and Stewart (2001).

If the Kuiper belt was not excited by resident planetary embryos, then what mechanism excited and depleted the Kuiper-belt population in the early Solar System? As discussed in the Introduction, the massive Neptune-scattered planetesimal scenario (Morbidelli and Valsecchi 1997) has the problem of not preserving many Plutinos, relative to the classical-belt population (Petit *et al.* 1999). Unless the estimate of the relative Plutino population is further reduced in the future (it has been decreased already from an early 30% down to 4%), this scenario seems unlikely. The sweeping resonance models are not able to provide enough excitation to the classical-belt population (Malhotra 1995). The passing star scenario (Ida *et al.* 2000) and the Thommes *et al.* (1999) scenario remain as the only alternatives. A passing star can explain the absence of bodies with moderate eccentricity beyond 50 AU, but it cannot account for the observed inclination distribution, unless it strongly perturbed the planetary system also (Levison, private communication, 2001). One can conjecture that the planets' eccentricities and inclinations have been subsequently dumped by dynamical friction, but it is questionable if enough mass was still available in the planetary region in the form of small planetesimals. The Thommes *et al.* (1999) scenario—according to which Neptune experienced a high-eccentricity phase during which it repeatedly crossed the Kuiper belt—can explain the bimodal inclination distribution of Kuiper-belt objects (Brown 2001) and the correlation between inclination and size of the bodies (Levison and Stern 2001). However, some issues—such as the preservation of a significant Plutino population and the existence of a yet undiscovered cold disk at sufficiently large heliocentric distance—need to be explored further. In summary, the primordial sculpting of the Kuiper belt remains an intriguing open problem.

Finally, from our study, we can provide some rough indication of the maximal size of bodies still present in the transneptunian

region. For this purpose, we take as example cases the orbital distribution of the embryos at the end of our simulations, attributing to all the embryos a given radius or absolute magnitude, and running our Monte Carlo model to compute the probability of detection of at least one object. If we assume Pluto-size bodies with 0.04 albedo, the probability of detection of at least one object is 10, 22, 62, 74, and 100%, respectively, for the orbital distributions corresponding to the end of simulations #1 to #5. This implies that it is unlikely that many (order 10) Pluto-size bodies exist on moderately excited classical belt orbits, with semimajor axis smaller than about 70 AU (as in simulations #3 to #5). Conversely, the existence of Pluto-size bodies on very eccentric and long periodic orbits—typical of the scattered disk or the extended scattered disk—is consistent with the lack of observations. On the other hand, if we assume an absolute magnitude of 4 (roughly 1000 km for a 0.04 albedo), the probability of detection of at least one object is 3, 6, 11, 20, and 98%, again for the orbital distributions of simulations #1 to #5. Two objects are known in the Kuiper belt with $H < 4$: Varuna ($i = 17.1$, $e = 0.055$, $a = 43.293$) and 2001 KX76 ($i = 19.7$, $e = 0.246$, $a = 39.293$). This suggests that some 30 bodies of this type can exist on moderately excited orbits, of the type shown in the bottom right panel of Fig. 2 (simulation #5). We remark that, for this orbital distribution, the entire 98% discovery probability is carried by the Spacewatch survey, and Varuna has indeed been discovered by Spacewatch.

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