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Early dynamical evolution of the Solar System: constraints from asteroid and KBO dynamics

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Abstract. The orbital distribution of asteroids and Kuiper-belt objects (KBOs) provides important information for the dynamical evolution of the solar system. Recent advances in modelling the dynamics of asteroids and KBOs have increased our understanding of the mechanisms responsible for the main features observed in the small-body belts. There are, however, several pieces left to complete the puzzle of the dynamical history of the solar system. In particular, we now understand that the solar system probably looked very different during the first $500-1000$ Myr than today, mainly because of two processes that took place during those times: (i) planetary formation and (ii) planetary migration. I will discuss observational and dynamical constraints that any model, attempting to reconstruct this early period, should obey. I will then present a new model for planetary migration, which successfully reproduces the observed orbital distribution of the trans-Neptunian objects. I will then discuss the implications of this model on the early evolution of the inner solar system, in particular the distribution of main-belt asteroids and the bombardment of the terrestrial planets by small bodies.

1. Introduction

The belief that our solar system has been, and for ever will be, in a steady dynamical state has been strong among dynamicists for several centuries. The prediction of periodic phenomena, such as the transits of Venus and Mercury across the solar disc, were considered as the great success of "old" celestial mechanics. More complex types of dynamical behaviour, although noted by Poincaré (1892), were considered merely as insignificant exceptions. Today, we know that the situation is most likely quite the opposite. Chaos is the rule rather than the exception in solar system dynamics. New methods and tools of celestial mechanics have been devised in order to cope with these phenomena, resulting in remarkable advances over the last 20 years. I mention only the discovery of the mildly chaotic motion of the planets (Sussman & Wisdom 1992; Laskar *et al.* 1993) and the explanation of the origin of the Kirkwood gaps in the distribution of asteroids (for a review see Moons 1997).

It is fair to say that we now understand quite well the dynamical evolution of the system over the last ∼4 Gy. It is, though, intriguing that, despite our advanced analytical and numerical tools, a mathematical proof of the stability of the planetary system for such long time scales has not been obtained so far. On the other hand, our analytic and semi-analytic theories have been well tested by sophisticated numerical experiments, largely aiming to explain the "strange" motions of the thousands of asteroids and comets that reside in the system. Small bodies are mainly contained in two large reservoirs: the main asteroid belt and the Edgeworth-Kuiper belt. These belts provide a unique laboratory for dynamics, since the number of bodies observed over the last 100 years is very large and their orbital distribution is known with very good accuracy. The long term effects of gravitational perturbations, exerted by the planets on the small bodies, are imprinted in these distributions. The goal of "new" celestial mechanics is evident: to extract as much information as possible from these distributions, by "reading between the lines", in order to unveil clues about their dynamical evolution. As will be described in the following sections, the strongest long-term effects of the planets, especially on the asteroid belt, are now well understood. There are, however, many observed features, primarily in the distribution of trans-Neptunian objects, which cannot be understood in the framework of a steady-state planetary system. These dynamical features were most likely created during earlier epochs in solar system evolution.

There are two main phases of early solar system evolution during which the dynamics of the planets and the small-body belts were drastically different than over the last ∼4 Gy. They are related to two main processes: (i) planet formation and (ii) planet migration. The formation of the gas giants probably took place during the first $\sim 1 - 10$ Myr, when the proto-solar gas nebula was still massive enough and the dynamics were dominated by the interactions of the planets with the gas disc (see Pollack *et al.* 1996; Lubow *et al.* 1999). Planetary migration could also have taken place during this phase (see Ward 1997; Lyn & Papaloizou 1986; Masset & Papaloizou 2003). However, whether this really happened (and to what extent) in our solar system can only be shown by extremely expensive numerical simulations, which are also quite dependent on a more or less accurate knowledge of the relevant physical parameters of the system at that time (e.g. mass of the disc, physical size, aspect ratio, initial positions and masses of the planets, etc.). This is the reason why this particular phase is the most difficult to tackle and remains still one of the "hottest" research areas of dynamics of planetary systems. Understanding the wide variety of physical and dynamical properties among the observed extra-solar systems, demands a better understanding of this first phase of evolution of planetary systems.

After the formation of the gas giants was over and most of the gas disc was dissipated, a new epoch of gas-free dynamics began. At that time the solar system contained (i) the four outer planets (Jupiter, Saturn, Uranus and Neptune), (ii) a large disc of solid *planetesimals* (∼10-km-sized bodies, see Weidenschilling 2003), likely extending all the way from the inner edge of the solar system (∼0.5 AU) to even beyond the currently observed Kuiper belt (∼50 AU) and possibly (iii) a number of lunar-sized solid bodies, called planetary embryos, which are presumed to have been the building blocks of the terrestrial planets (Chambers 2001; also Petit *et al.* 2001). It is now widely accepted that Uranus and Neptune must have formed much closer to the Sun than is currently observed, in order for their core-accretion time scales to be have been shorter than the time scale of nebula dissipation (∼10 Myr). Thommes *et al.* (1999) suggested that the initial orbital radii of these two planets must have been much smaller than ∼20 AU. Even if the exact locations of the giant planets at that epoch are poorly constrained, it is evident from the above results that they must have migrated a lot! A quite efficient mechanism of planetary migration, caused by the scattering of leftover planetesimals – contained in the interplanetary region and the external disc – by the planets, was first described by Fernandez & Ip (1984). Its efficiency was clearly demonstrated by the numerical simulations of Hahn & Malhotra (1999).

The question that we focus on now is the following: Is it possible for this early process of large-scale planetary migration to have left some traces behind and how can we identify them? In the following I am going to review recent results supporting the following answer to the above question: "Yes, at least in the orbital distributions of the small bodies". The relevant observational features and the constraints they imply, concerning the early dynamical evolution of the solar system, are presented in this paper.

2. The asteroid belt

The number of asteroids discovered in the inner solar system increases every day. The numbered objects, whose orbits are determined to an accuracy that allows us to speak of "well-known" objects, are now of the order of 100 000 (http://hamilton.unipi.it/cgi-bin/astdys/astibo). Spectroscopic and rotation properties are known for far fewer objects, but the results of on-going surveys are encouraging. The current status of our knowledge is well summarized in the *Asteroids III* book (edited by Bottke *et al.* 2002), so I will restrict myself here to presenting information that are most relevant to the present work.

The vast majority of asteroid orbits lie between Mars and Jupiter, in a region called the *main belt.* The semi-major axes of main-belt asteroids are $2.0 \leqslant a \leqslant 3.6$ AU, their eccentricities are typically smaller than $e \sim 0.3$ and the inclinations of their orbital planes with respect to the ecliptic are smaller than $i \sim 20°$. The current total mass of the main belt is estimated to be $\sim 5 \times 10^{-4}$ Earth masses (M_E), which is at least 1000 times smaller than what the minimum mass solar nebula model predicts (Petit *et al.* 2001). Thus, today's main belt is just the remnant of a largely depleted primordial belt. Petit *et al.* (2001) have shown that most of this depletion could have taken place during the first ~100 Myr of the solar system's life, during the formation of the terrestrial planets. It is important to remember that the main belt is the main source of the short-lived Near-Earth asteroids (NEAs), which leak out from the belt and spend ~10 Myr in the near-Earth space as a result of resonant perturbations, induced by the major planets, and close encounters with the terrestrial planets. This implies that the primordial, more-massive main belt was producing more NEAs, thus leading to a much larger number of impacts with the Earth than at present.

Fig. 1 shows the distribution of all numbered main-belt asteroids, as a function of their orbital elements, (a, e, i). This non-uniform distribution has been a puzzle for many years. The most prominent observable features are the Kirkwood gaps, which are associated with mean motion resonances (2:1, 7:3, 5:2, 3:1 and 4:1) between Jupiter and an asteroid. It has been shown that the dynamics in these resonances are chaotic, and primordial asteroids would have had plenty of time to slowly change their eccentricities and reach perihelion (aphelion) distances that would lead them to close encounters with the inner (outer) planets and subsequent ejection from the solar system. Other resonant phenomena, such as secular resonances between the precession frequencies of the asteroids and the planets, have also sculpted the distribution of asteroids. Note, however, that the locations of the resonances depend on the semi-major axes of the planets. Thus, to zeroth order, we could say that the current main belt distribution does not seem to contain information about the early phases of the solar system, in particular the era of planetary migration. As we will see in following sections, this is not true.

I should point out that recent results have revealed the importance of the long-term effects of two, "slow," still on-going processes: (i) chaotic diffusion, generated by a great number of thin resonances that criss-cross the belt and (ii) the Yarkovsky thermal force, which slowly changes the semi-major axis of small asteroids, thus leading them to cross several resonances. These two phenomena play an important role in transporting NEAs and meteorites to Earth, as well as in shaping the asteroid families (see the relevant chapters in *Asteroids III*).

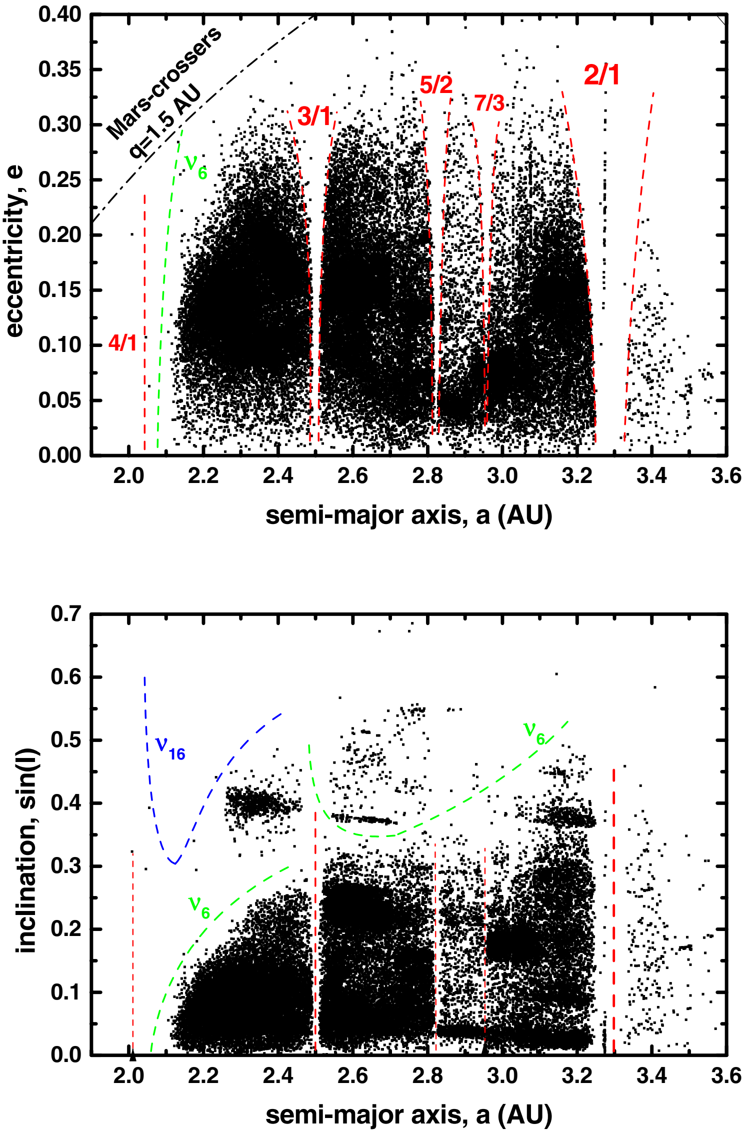

Figure 1. Distribution of main-belt asteroids in the (a, e) (top) and (a, i) (bottom) planes. The main mean motion resonances with Jupiter are indicated by "V"-shaped curves (top), which approximately define the width of each resonance zone. The location of first-order secular resonances (ν_i's), between the frequency of precession of the pericenter (grey) or the node (black) of an asteroid and the corresponding frequency of Saturn are also shown. Note how the locations of the resonances coincide with gaps in the distribution of asteroids.

3. The trans-Neptunian belt(s)

The first trans-Neptunian object was discovered by Jewitt & Luu (1993). Nowadays we know with a good accuracy the orbits of ~1000 objects. Their distribution is shown in Fig. 2. The trans-Neptunian objects are divided among several groups, depending on the dynamical characteristics of their orbits:

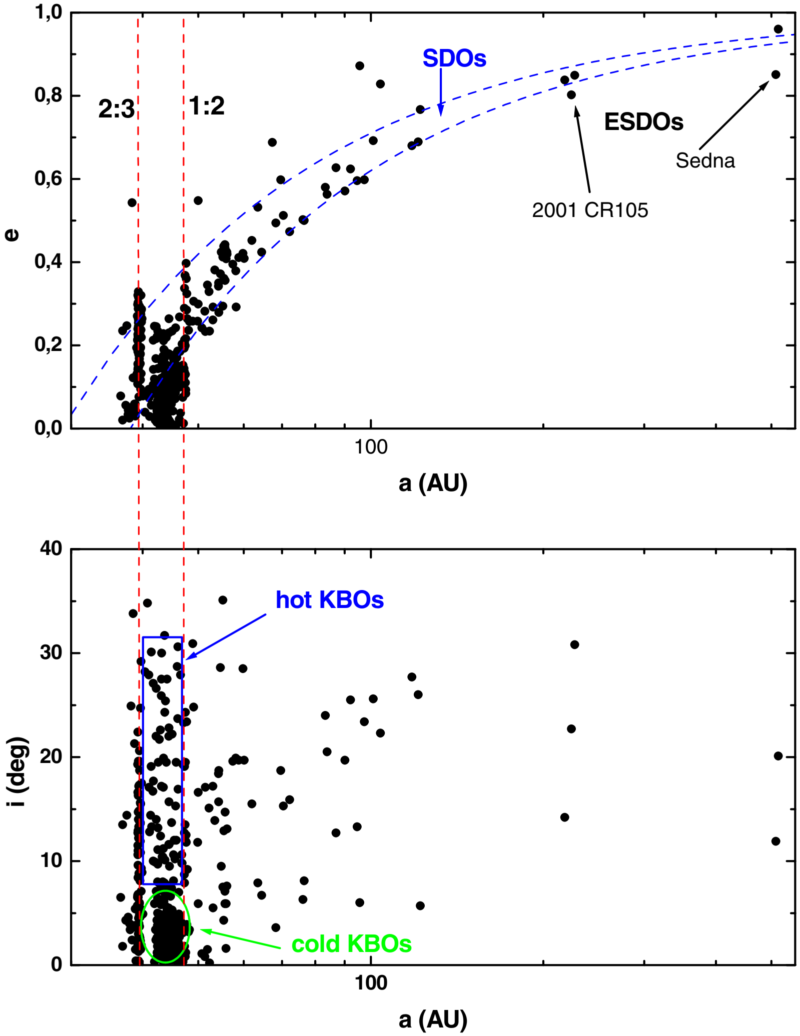

Figure 2. Distribution of the trans-Neptunian objects in the (a, e) (top) and (a, i) (bottom) planes. Lines of constant perihelion distance $q = 30$ AU and $q = 39$ AU are drawn in the top panel, to distinguish SDOs from ESDOs. The locations of the main mean motion resonances with Neptune are indicated by the vertical lines.

- The *"classical" Kuiper Belt objects* (KBOs) have orbits with $40 \leqslant a \leqslant 50$ AU and $0 \leqslant e \leqslant 0.2$. These are stable orbits, since the KBOs are neither in a low-order resonance nor do they approach Neptune (Duncan *et al.* 1995). Frequently we distinguish between dynamically "cold" KBOs, which have $i \leqslant 5°$, and "hot" KBOs ($i > 5°$). This distinction seems to be also consistent with different spectroscopic properties (Brown 2001; Trujillo & Brown 2002). I should also point out that the apparent edge of the classical belt at ∼50 AU is most likely real. If a significant number of bodies in low-e orbits existed beyond 50 AU, the observational surveys would have detected at least a few of them by now. Several mechanisms have been proposed to explain the truncation of the primordial disc, including an early close stellar passage (Ida *et al.* 2000; Kobayashi & Ida 2001).

- The *Resonant objects* are trapped in a mean motion resonance with Neptune. The most well-known are the so-called *Plutinos* which, like Pluto itself, are captured in the 2:3 resonance. The resonant objects are estimated to be ∼7% of the total population. Malhotra (1995, 1996) was the first to show that the Plutinos could have been adiabatically captured into resonance, during Neptune's migration.
- The *scattered disc objects* (SDOs) have orbits with high semi-major axes and eccentricities and their perihelion distances are roughly between 30 and 39 AU. Thus, they can have close encounters with Neptune. In fact, this is considered to be the origin of the SDOs: they were scattered to high-e orbits by Neptune, as it was migrating outwards. I should note that SDOs were predicted theoretically by Duncan & Levison (1997), before being observed (Luu *et al.* 1997), as the most likely source of Jupiter-family comets.
- The *extended scattered disc objects* (ESDOs) also have high values of a and e, but their perihelion distances are larger than 40 AU. The most famous ESDOs are 2000 CR105 and *Sedna* (former 2003 VB12, Brown *et al.* 2004). Their large perihelion distances imply that they are not coupled to Neptune. That is exactly the problem of their origin: if they originated from the scattered disc, then an "extra" torque is required to decouple them from the planets. A number of possible solutions have been recently proposed by Morbidelli & Levison (2004).

It is interesting that, with the exception of the classical KBOs, the origin of all other groups is linked to the migration of Neptune. Thus, before discussing the formation of the KBOs, I will review recent results on planetary migration in our solar system.

4. Planetary migration

Let me briefly describe the process of planetary migration by planetesimal scattering. The principle of this process was first demonstrated by Fernandez & Ip (1984) and was later used by Malhotra (1995, 1996) to explain the origin of the Plutinos.

Suppose that a small particle with $a > a_{Nep}$ approaches Neptune, i.e. it has an eccentricity such that its orbit intersects the one of Neptune. Then, a close encounter with Neptune can decrease its semi-major axis. Conservation of angular momentum implies that Neptune should increase its own semi-major axis by a very small amount. A subsequent encounter may have the inverse effect, so that the net change of Neptune's semi-major axis would be zero. On the other hand, if the encounter is so effective that the particle is ejected to Oort cloud distances on a hyperbolic orbit, then the net change of Neptune's semi-major axis is negative.

However, when more than one planet exists in the system, the majority of the disc particles have a different evolution; this is true for our own system. The first encounter with Neptune, which decreases the particle's semi-major axis, can deliver the body to a Uranus-crossing orbit. Then, Neptune's small increase in a_{Nep} becomes permanent. Similarly, Uranus may hand over the particle to Saturn, and then Saturn to Jupiter. Jupiter, having a much larger mass than the other planets, ejects all particles to hyperbolic orbits. Thus, the net effect on the four-planets system is: Saturn, Uranus and Neptune move outwards, while Jupiter moves inwards. This was indeed observed in simulations, first by Hahn & Malhotra (1999). The speed of migration is roughly inversely proportional to the mass of the planet, but also depends on the orbital separation between planets, as the latter determines the efficiency of the "passing" mechanism. Thus, Neptune moves faster than any other planet, Uranus moves much slower than Neptune but still faster than

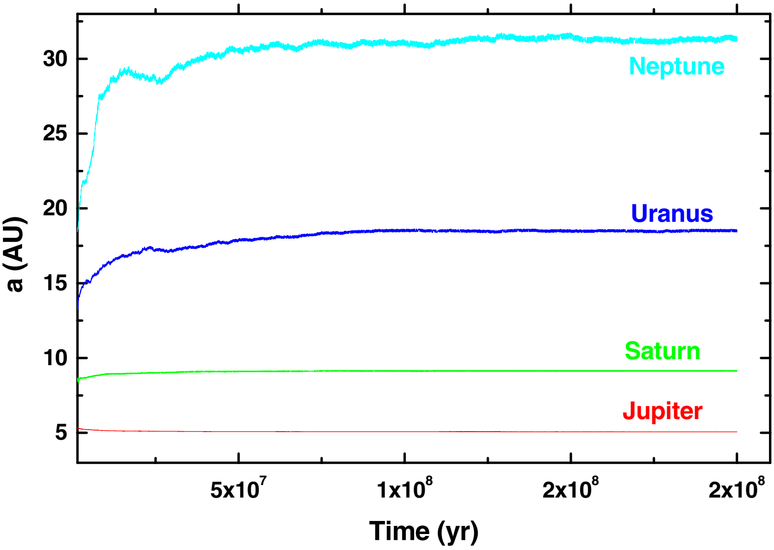

Figure 3. Evolution of the semi-major axes of Jupiter, Saturn, Uranus and Neptune as functions of time. Taken from an $N-$body simulation of planetary migration in a disc of 50 Earth masses (represented by 1000 equal-mass tracer bodies). The final values of a are very close to the observed ones for all four planets.

Saturn, while Jupiter has the smallest absolute variation in a. The result of a numerical simulation is shown in Fig. 3.

The migration of Neptune could generate the populations of SDOs and resonant objects. The most important component of the trans-Neptunian population – the KBOs – seems, at a first glance, not to be related to this process. Yet, its formation is still a mystery for solar system science. Fig. 4 shows a series of "snapshots", taken from a numerical simulation of planetary migration. The creation of a scattered disc, from an initially "cold" disc, is shown. Note also that, despite the fact that the disc was initially truncated at 30 AU, at the end of the simulation a few classical KBOs were also found in the 40 – 50 AU region. Obviously they were somehow transported outwards, during the migration of the planets.

5. Building the classical Kuiper belt

What is the origin of the classical KBOs? The obvious answer is: they were formed right where they are now. However, this solution opens the door to another problem (don't they always?). The total mass of the initial disc needed for the currently observed number of KBOs to have accreted *in situ* is too big (Stern 1996), compared to the observed mass (Jewitt *et al.* 1996; Chiang & Brown 1999). Two mechanisms have been proposed for getting rid of this extra mass: (i) dynamical elimination by Earth-sized planetary embryos (Morbidelli & Valsecchi 1997), or (ii) collisional grinding (Stern & Colwell 1997; Davis & Farinella 1998). However, they both lead to the same problem: if Neptune was migrating in this massive disc that was extending possibly beyond 50 AU, would it still stop at 30 AU?

According to the results of Gomes *et al.* (2004), the answer to the above question is no! For a disc as massive as necessary to form KBOs at 50 AU, Neptune would have migrated

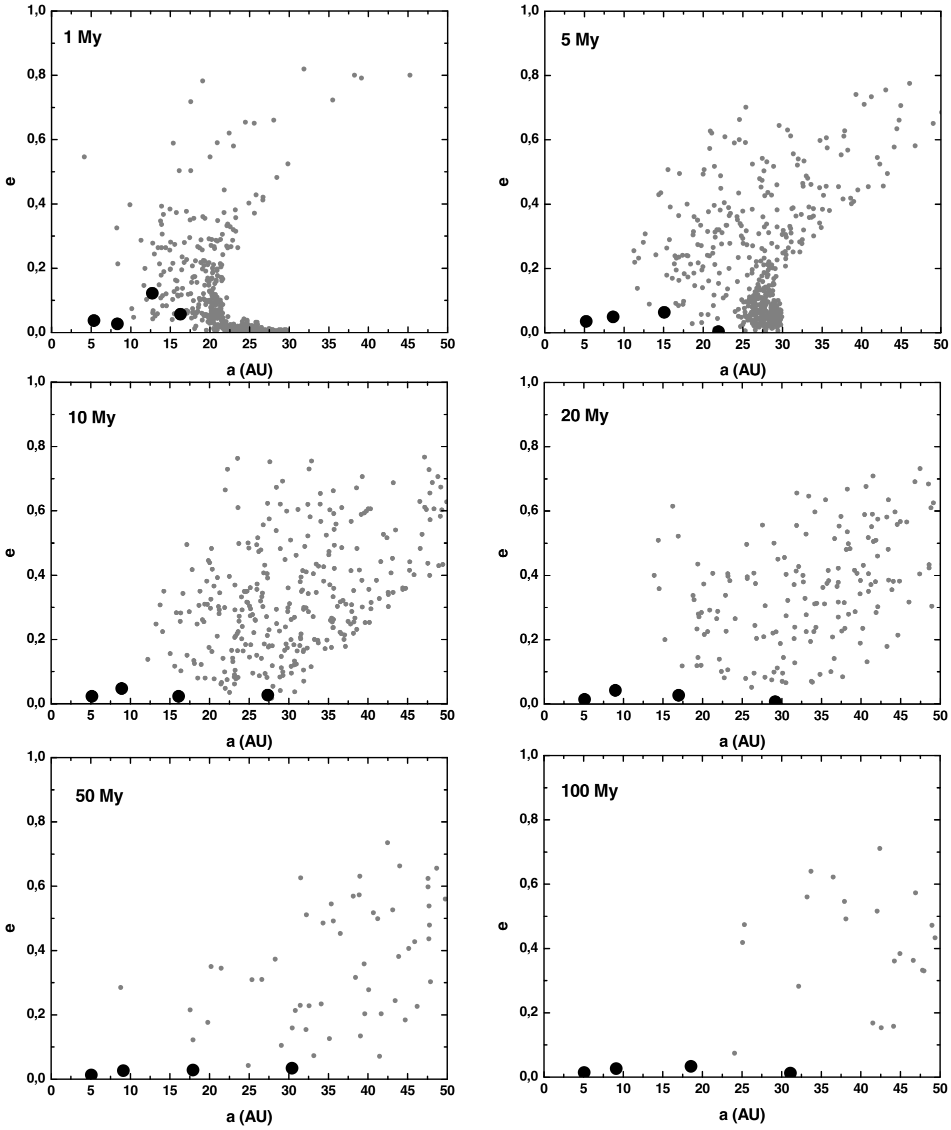

Figure 4. Planetary migration in a disc of planetesimals. Six snapshots of a simulation are shown: at $t = 1\,$Myr, 5 Myr, 10 Myr, 20 Myr, 50 Myr and 100 Myr. The variation of the semi-major axes of the planets is apparent. In this simulation, the disc contained initially ~50 Earth masses. At the end of the simulation (100 Myr), less than ~4 Earth masses are still present, mostly in the scattered disc. Note that, despite the fact that the disc was originally truncated at 30 AU, a few classical KBOs with $a > 40\,$AU seem to be present at the end of the simulation. They were most likely transported there by the mechanisms described in Gomes (2003) and Levison & Morbidelli (2003). Note however that the resolution of this experiment is not adequate to correctly represent resonance trapping (see Gomes *et al.* 2004). Thus, very few objects were found to be transported by resonances.

all the way to the edge of the disc. It is thus more likely that the planetesimals' disc was somehow truncated near ~35 AU, which means that there was never enough mass to form the KBOs *in situ*. An alternative idea for the origin of the KBOs, proposed by Gomes (2003) and Levison & Morbidelli (2003), is that they formed in the same region as Uranus and Neptune, i.e. much closer to the Sun than now, and were transported outwards during planetary migration. We note that the mechanism proposed by Gomes (2003) explains the origin only of the "hot" KBOs, while the mechanism of Levison & Morbidelli (2003) explains the origin of the "cold" KBOs.

Gomes (2003) performed numerical simulations, in which he observed that, as Uranus and Neptune migrated outwards, objects that were scattered away to high values of e and i were temporarily getting captured into resonance with Neptune. As Neptune was moving towards 30 AU, objects were constantly penetrating the "hot" classical KBOs region, being released from resonance at different values of e and i. The most unstable ones could not have survived for the age of the solar system. However a small, but sufficient, number of objects, with orbits similar to the ones of the "hot" KBOs, were produced.

Levison & Morbidelli (2003) started by asking themselves why the edge of the "cold" Kuiper belt almost coincides with the location of the 1:2 resonance ($\sim$48 AU) with Neptune. This observation led them to perform a number of numerical simulations, during which they observed that objects, initially following "cold" orbits (e, $\sin i \sim 0$) exterior to the one of Neptune but interior to 30 AU, were getting trapped and "pushed out" by the 1:2 resonance. Particles that were from time to time released from the resonance had eccentricities ranging from 0.8 down to zero. The low eccentricity objects developed stable orbits, very similar to those of the "cold" KBOs. Note that the 1:2 resonance does not excite the inclinations. Thus, mostly "cold" objects were created in the simulations of Levison & Morbidelli (2003).

The low efficiency of these two mechanisms, along with the results of Gomes *et al.* (2004), suggest a new scenario for planetary migration, in which Neptune was initially interior to $\sim$18 AU and the disc of planetesimals was truncated at $\sim$30 AU. The question now is: what is the effect of this planetary migration model on the orbital structure of the asteroid belt?

6. Depletion of the asteroid belt

As mentioned in section 2, the current mass of the asteroid belt is estimated to be at least 1000 times smaller than its initial one. The largest part of the implied depletion is supposed to have taken place during the formation of the terrestrial planets. Petit *et al.* (2001) have shown that proto-planetary embryos, residing at that time in the belt, would have excited the orbits of the asteroids, forcing more than 99% of these bodies to escape. The remaining asteroids would have achieved a distribution in the (a, e, i) space, similar to the current one.

Levison *et al.* (2001) have shown that, if the migration of the outer planets occurred early on when the asteroid belt was still dynamically "cold", the asteroid belt would have been almost completely depleted! The reason for this catastrophe is that, as the planets move, a strong 1:1 resonance between the perihelion precession frequency of an asteroid and the one of Saturn (called the ν_6 resonance) would have swept across the belt. The effect of this resonance would be to increase the eccentricity of any asteroid from 0 to nearly 1, thus placing the asteroid on a planet-crossing orbit. This phenomenon poses a serious problem for any migration scenario.

However, if the migration of the outer planets happened somehow late, the effect of the ν_6-sweeping may not have been the same. Assume that the belt was not dynamically "cold", but was already pre-excited by the mechanism described in Petit *et al.* (2001), during terrestrial planet formation and before the migration of the outer planets had started. Then, as the ν_6 resonance was sweeping the belt, different asteroids would

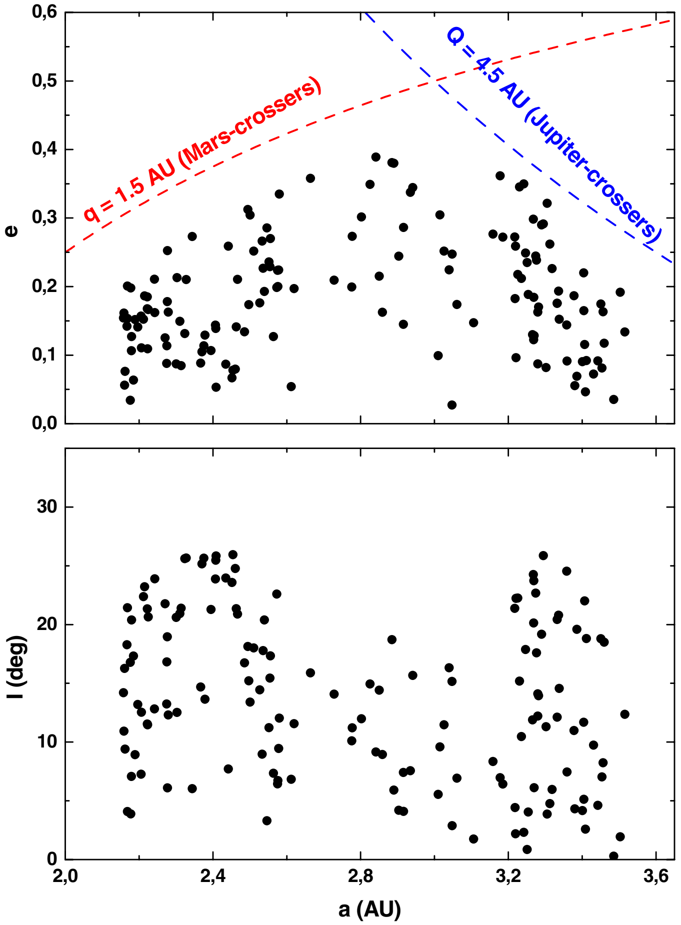

Figure 5. Depletion of the asteroid belt. The distribution of the fictitious asteroids, originally in pre-excited orbits, that survive planetary migration is shown. The shape of this remnant asteroid belt is close to the observed one. Main-belt asteroids reside on orbits that cross neither Mars's orbit, nor that of Jupiter, i.e. their perihelion distance is $q > 1.5$ AU, and their aphelion distance $Q < 4.5$ AU. The two limiting curves, $q = 1.5$ AU and $Q = 4.5$ AU are superimposed on the (a, e) plot.

encounter the resonance at different eccentricities and perihelion orientations. This "mixing" of initial conditions would lead to a "mixed" evolution, in which some asteroids would have had their eccentricities increased and some decreased. Provided that resonance sweeping occurred sufficiently fast, comparable numbers of high-e (unstable) and low-e (stable) asteroids would have been produced by this process. This orbital "mixing" could not have occurred if the belt was "cold" (all asteroids having $e \sim 0$); the resonance would have increased the eccentricities of all asteroids.

We simulated this process by integrating the orbits of Jupiter, Saturn and 1000 fictitious asteroids, initially on orbits with $2.0 \leqslant a \leqslant 4.0$, $0 \leqslant e \leqslant 0.3$ and $0° \leqslant i \leqslant 20°$.

An analytic prescription of the migration drag-force was built in the code (Malhotra 1996), in order to force the planets to migrate with the desired rate. For migration times of ∼10 Myr, we found that ∼10% of the asteroid belt survived. More importantly, the orbital distribution of the surviving bodies was close to the one currently observed. This is shown in Fig. 5. Thus, we can conclude that, in order to be able to observe today an asteroid belt, with its current shape, the migration of the outer planets must have occurred late, after the formation of the terrestrial planets was almost complete, i.e. ∼100 Myr after the formation of the Sun.

7. Open problems

Despite the long list of exciting new results that have been recently published by several authors and I have presented in this paper, it would be naive for me to argue that we have unveiled the early dynamical evolution of the solar system. There are still a number of important issues to be answered that could help us to link all parts of the story and come up with a self-consistent model. In this last section I will only mention two that I believe are the most important ones and speculate on possible solutions, in agreement with the above mentioned results. These two problems are: (i) the observed orbital configuration of the outer planets, and (ii) the Late Heavy Bombardment of the Moon (LHB).

Although the “standard” migration scenario can explain the large-scale variation of the semi-major axes of the outer planets, it does not reproduce the eccentricities and mutual inclinations of their orbits, which go up to 9% and 2° respectively. The reason is that, during migration, the planetesimals exert on the planets a significant amount of dynamical friction, which damps the eccentricities and inclinations to zero. Thus, some excitation mechanism needs to act, during migration, in order to end up with the correct planetary orbital configuration in all three elements. This yet unidentified mechanism can be either (i) encounters between the planets, or (ii) a resonant interaction. A possible, but rather violent version of (i) has been studied by Thommes *et al.* (1999). However, it requires a very massive disc to stabilize the planetary system, which is not consistent with some of the results presented in the previous sections. The second mechanism (resonance) seems more appealing and has to be explored in detail.

Probably the most well known observational fact about the solar system is the existence of the large basins on the surface of the Moon. The analysis of rock samples taken by the Apollo mission suggests that the basins were formed during an intense phase of bombardment of the Moon, around 3.9 Gyr ago. This cataclysmic event is usually referred to as the Late Heavy Bombardment (LHB). However, other evidence does not support this cataclysm and seems to favour an alternative evolution scenario, in which the bombardment was very heavy even from the formation of the Moon, and suddenly ended around 3.9 Gyr ago. For a comprehensive review see Hartman *et al.* (2000; also Kring & Cohen 2002). It is clear that more evidence is needed to resolve this conflict. However, a few arguments can be made from the point of view of dynamics. It is frequently stated that the LHB is very difficult to reproduce by a dynamical model. This is not correct. Levison *et al.* (2001) have shown that a late formation and migration of Uranus and Neptune could provide the estimated mass of LHB projectiles, in the form of comet-like bodies originating from the outer planetesimal disc. Moreover, as shown in the previous section, an important amount of mass (a few times the current mass of the asteroid belt) would become NEAs during planetary migration. More results are needed in order to quantify the efficiency of mass delivery from both sources. More importantly, we still have to understand if and how planetary migration could be delayed, in order for the bombardment to occur ∼600 Myr after the formation of the Moon.

As a conclusion, I think that the results reviewed in this paper are very encouraging. A comprehensive model for the late phases of planetary migration by planetesimal scattering and the sculpting of the small-body reservoirs is close to be completed. It seems that the community is close to understanding the early dynamical evolution of the solar system. That is, of course, if we consider as “time zero” the time at which no gas is left anymore in the solar system. The evolution of the planetary system during the gas-dominated phase, i.e. the first ∼10 Myr after the formation of the Sun, still remains largely unknown. I believe that linking these two epochs is the big task for solar system dynamics in the next decade; it is a fascinating time to be in this line of work!

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Discussion

BERNARD DE SAEDELEER: Are the planets are still migrating?

KLEOMENIS TSIGANIS: Now? No, because there's no mass left to drive the migration. There are bodies encountering Neptune – this is the scattered disk. But the planets are now far apart, so the chain of passing particles from one planet to another is broken.

CHRISTINE ALLEN: I'm concerned by your saying that the disk gets truncated at 50 AU by a passing star. Work we have done in Mexico shows that passing stars will begin to truncate the distribution of semi-major axes at about 3000 AU for that age.

KLEOMENIS TSIGANIS: You mean by stars as they are now distributed in the galaxy?

CHRISTINE ALLEN: Or as they were millions of years ago.

KLEOMENIS TSIGANIS: Recent simulations show that if a star passed near enough within the Oort cloud, it could truncate the disk exactly at 50 [AU]. I haven't done the simulation myself, but it seems possible. Of course, you have to understand that people advocating these arguments assume that the Sun was most likely formed in a very small cluster, and that this truncation event happened very early.

MIKHAIL MAROV: With the recent discovery of the large bodies in the Kuiper Belt – bodies such as Quaoar and Sedna – do you think still that there has been mass depletion in the Belt? And that there is still something like less then the mass of the Earth for the total mass of the Belt? It is possible that a large-size body could be still found. I don't know whether you will designate them as cold or hot bodies.

KLEOMENIS TSIGANIS: They are scattered disk bodies. They have very eccentric orbits.

MIKHAIL MAROV: That's what I mean - bodies with very eccentric orbits. This is possibly the reason why we haven't found them yet.

KLEOMENIS TSIGANIS: I said that there would be no bodies outside 50 AU for the classical Kuiper Belt. With the surveys done, compiled and de-biased, it seems that if there were big bodies on low-inclination eccentric orbits, they would already have been discovered. Now these bodies – Sedna, for example – are scattered disk bodies in highly eccentric orbits. The total mass of the scattered disk is estimated to be more or less the same as the Kuiper Belt, so a few hundredths to a few tenths of an Earth mass.

Mikhail Marov: You did not mention that the idea that Uranus and Nepture formed very close to the Jupiter-Saturn position was first put forward by Safronov and his school at the beginning of the 80s. It was made because the very specific composition of Neptune and Uranus can hardly be explained in terms of the current position of formation of these bodies. A second comment: I disagree a little with the estimate which you drew in your presentation for the LHB projectiles. You quoted something like $7 - 10 \times 10^{22}$ g for Earth. In our publication we estimated a bit more; it's quite comparable to the mass of the Earth's ocean, so in the last phase of the heavy bombardment it can be possible to explain even the mass of the Earth's ocean.

Kleomenis Tsiganis: Yes, the estimates that I used are from the recent paper by Levison *et al.* (2001). If I remember correctly, the estimate for the Earth and Mars are more or less the same, which would provide Mars with atmospheric water, but not the water of an ocean. The latest papers that I used as a base for this calculation provide something like 5% of the ocean.

Mikhail Marov: It's important because we've found that it was even comparable in size to the mass delivered by the cometary-like bodies. So this is an explanation for the early ocean on all terrestrial bodies.

Kleomenis Tsiganis: There is an alternative solution for the water on Earth which refers to the first phase of depletion of the asteroid belt – by the end of the formation of the Earth, a lunar-size body encounters the Earth and provides the oceans.

Mikhail Marov: I am not in favour of the idea that it was direct bombardment from the Kuiper Belt to the inner planets. The major part comes first from Jupiter orbit-crossers.

Kleomenis Tsiganis: Of course ... Jupiter family comets coming from the disk.

Floor van Leeuwen: During those first 100 million years the Sun itself goes through quite a violent phase of its evolution. If the observations of the Pleiades and Orion are anything to go by, then it has gone through a phase of very rapid spin-up, just before becoming an actual main sequence star, followed by a short period of release of angular momentum – very strong magnetic fields going through the whole system. This angular momentum is comparable to the whole angular momentum of the solar system. Where does that feature in your scenario?

Kleomenis Tsiganis: Nowhere.

Floor van Leeuwen: Nowhere? That's the problem! I have seen these scenarios being put out year after year. These phenomena have been known for years and it doesn't seem to penetrate this whole formation of the solar system story.

Kleomenis Tsiganis: I skipped the first 10 million years, because even the gas alone with the quiet Sun is a big problem for doing a dynamical model that could be handled, even numerically. We are now trying to understand more deeply these effects of gas and radiation. But this is really an embryonic stage for the dynamicist, because we do not know these phenomena well enough to simulate them, for the moment. So slowly we are getting there.