Evidence from the asteroid belt for a violent past evolution of Jupiter's orbit

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Received by AJ, on may 24, 2010; accepted by AJ, on Sept 8, 2010

ABSTRACT

We use the current orbital structure of large (> 50 km) asteroids in the main asteroid belt to constrain the evolution of the giant planets when they migrated from their primordial orbits to their current ones. Minton & Malhotra (2009) showed that the orbital distribution of large asteroids in the main belt can be reproduced by an exponentially-decaying migration of the giant planets on a time scale of $\tau \sim 0.5$ My. However, self-consistent numerical simulations show that the planetesimal-driven migration of the giant planets is inconsistent with an exponential change in their semi major axes on such a short time scale (Hahn & Malhotra, 1999). In fact, the typical time scale is $\tau \geq 5$ My. When giant planet migration on this time scale is applied to the asteroid belt, the resulting orbital distribution is incompatible with the observed one. However, the planet migration can be significantly sped up by planet-planet encounters. Consider an evolution where both Jupiter and Saturn have close encounters with a Neptune-mass planet (presumably Uranus or Neptune themselves) and where this third planet, after being scattered inwards by Saturn, is scattered outwards by Jupiter. This scenario leads to a very rapid increase in the orbital separation between Jupiter and Saturn that we show here to have only mild effects on the structure of asteroid belt. This type of evolution is called a jumping-Jupiter case. Our results suggest that the total mass and dynamical excitation of the asteroid belt before migration were comparable to those currently observed. Moreover, they imply that, before migration, the orbits of Jupiter and Saturn were much less eccentric than the current ones.

Subject headings: minor planets, asteroids: general planets and satellites: dynamical evolution and stability

1. Introduction

This paper is the third in a series in which we try to unveil the past evolution of the orbits of the giant planets using the current dynamical structure of the Solar System. In these works, we do not assume a priori any preferred model other than the well accepted fact that the giant planets were much closer to each other in the past and somehow moved towards their current orbital radii. This radial migration of the giant planets is believed to be the last major event that sculpted the structure of the Solar System (Levison et al., 2001; Gomes et al., 2005; Strom et al., 2005), an assumption which is implicit in our works.

In two previous studies, Morbidelli et al. (2009) and Brasser et al. (2009), henceforth labelled Paper I and Paper II respectively, we investigated how the giant planets (Paper I) and the terrestrial planets (Paper II) could have achieved orbits with their current secular properties i.e. with their current frequencies and amplitudes in eccentricity and inclination. The orbits of the planets are not fixed ellipses: they undergo precession, and the eccentricities and inclinations have long-term (secular) oscillations that, to a first approximation, are described by the Lagrange-Laplace theory:

$$e_k \exp(\iota \varpi_k) = \sum_j M_{j,k} \exp[\iota(g_j t + \beta_j)],$$
$$\sin(i_k/2) \exp(\iota \Omega_k) = \sum_j N_{j,k} \exp[\iota(s_j t + \beta_j)]. \quad (1)$$

Here ι is the immaginary unit and $e_k, i_k, \varpi_k, \Omega_k$ are, respectively the eccentricity, inclination, longitude of perihelion and longitude of the node of the planet k, g_j and s_j are the secular frequencies of the system (the index j running over the number of planets) and the coefficients M and N are the secular amplitudes.

In Paper I we concluded that close encounters between the giant planets is the only known mechanism that can explain the current amplitude of $M_{5,5}$ i.e. the excitation of Jupiter's eccentricity associated with the g_5 secular frequency. Other possible mechanisms, such as the crossing of multiple mean-motion resonances between Jupiter and Saturn, only excite $M_{5,6}$. Resonance crossings between Saturn and Uranus (which also kick Jupiter's orbit) are not strong enough to pump $M_{5,5}$ to its current value. However, a Neptune-mass planet (presumably Neptune itself or Uranus) encountering Saturn in general excites $M_{5,5}$ to values comparable to the current one. In principle, encounters of a planet with Jupiter do not need to have occurred. Planet-planet encounters are consistent with the giant planet evolution model of Thommes et al. (1999) and with the so-called "Nice model" (Tsiganis et al, 2005; Gomes et al., 2005).

In Paper II we focused our attention on the terrestrial planets. We showed that if the terrestrial planets were initially on quasi-circular, nearly-coplanar orbits, the divergent migration of Jupiter and Saturn must have been fast, otherwise the orbits of the terrestrial planets would have become too eccentric and/or inclined. Their excitation during giant planets migration is primarily caused by the crossing of the secular resonances $g_5 = g_2$ and $g_5 = g_1$, which pump $M_{2,k}$ and $M_{1,k}$. These resonances occur because g_5 decreases while the orbital separation between Jupiter and Saturn increases. More precisely, assuming that the orbital separation between Jupiter and Saturn increased smoothly as in Malhotra (1993, 1995) by

$$\Delta a(t) = \Delta a_{\rm now} - \Delta_0 \exp(-t/\tau), \qquad (2)$$

then τ had to be shorter than ~1 My in order for the terrestrial planets not to become too eccentric. We were concerned by such a short timescale, for the reasons detailed in sect. 2. So, in Paper II we identified a plausible scenario that resulted in a divergent radial displacement of the orbits

of Jupiter and Saturn that is rapid enough, although not of the smooth exponential form given in eq. (2), that we called the 'jumping-Jupiter' scenario. Here a Neptune-mass planet is first scattered inwards by Saturn and then outwards by Jupiter, so that the two major planets recoil in opposite directions. However, we were unable to firmly conclude that the real evolution of the giant planets had to be of the jumping-Jupiter type because of the following hypothetical alternative. Suppose that after their formation the terrestrial planets had more dynamically excited orbits than now (particularly with larger amplitudes $M_{1,k}$ and $M_{2,k}$). Their eccentricities could have been damped by the same mechanism that would have excited them if they had been nearly zero. In other words, the passage through the secular resonances $g_5 = g_2$ and $g_5 = g_1$, could have decreased the values of $M_{2,k}$ and $M_{1,k}$ to the current values, provided these resonance passages had occurred with the appropriate phasing.

The discussion on whether the orbital separation between Jupiter and Saturn increased smoothly, as in eq. (2) or abruptly (as in the jumping-Jupiter scenario) is not only of academic interest. These two modes of orbital separation correspond to two radically different views of the early evolution of our Solar System. In the first case, such evolution was relatively smooth, and the increase in orbital separation of the gas giants was driven solely by planetesimal scattering. In the jumping-Jupiter scenario, Jupiter was involved in encounters with another planet. In this case, the evolution of the outer solar system would have been very violent, similar to the one that is expected to have occurred in many (or most) extra-solar planetary systems.

In this work, we turn our attention to the asteroid belt. Similar to the terrestrial planet region, the migration of the giant planets drives secular resonances through the belt, but now

these are $g = g_6$ and $s = s_6$ (g and s denoting generically the pericenter and nodal precession frequencies of the asteroids, while g_6 and s_6 are the mean precession frequencies of Saturn). The radial displacement of these secular resonances affects the asteroids' local orbital distribution in a way that depends sensitively on the rate of migration (Gomes, 1997). Therefore, reproducing the current orbital distribution of the asteroid belt under different conditions can lead to strong constraints on how Jupiter and Saturn separated from each other. In addition the orbital properties of the asteroid belt might also provide information about the orbital configuration of the giant planets prior to their migration: it might help us constrain whether the pre-migration orbits of the giant planets were more circular or eccentric.

Recently, Minton & Malhotra (2009) showed that the orbital distribution of the asteroid belt is consistent with a smooth increase in the separation between Jupiter and Saturn. They assumed that, originally, the asteroids in the primordial belt were uniformly distributed in orbital parameter space and that the separation between the two gas giants increased as in eq. (2), with $\Delta_0 = 1.08$ AU (Malhotra, 1993) and $\tau = 0.5$ My. Unfortunately, different values of τ were not tested in that study nor did the authors offer any suggestions for a possible mechanism for this fast migration. Thus, in the first part of this paper we revisit Minton & Malhotra's work, with the aim of determining whether a value of τ as short as 0.5 My is really needed and what this implies. In sect. 2 we summarize the basic properties of planetesimal-driven migration that are important for this problem. In sect. 3 we investigate the evolution of the asteroid belt in case of a smooth, planetesimal-driven migration of Jupiter and Saturn. After we demonstrate the incompatibility between the orbital structure of the asteroid belt and this kind of migration, we describe the jumping-Jupiter scenario in sect. 4, followed by a presentation of its effects on the orbital structure

of the asteroid belt in sect. 5. The implications of this scenario are discussed in sect. 6, and the conclusions follow in sect. 7. In Appendix, we summarize the sequence of the major events that characterized the evolution of the solar system, as emerging from this and other works.

2. Brief description of planetesimal-driven migration

Planetesimal-driven migration occurs when a planet encounters a large swarm of planetesimals. The planet scatters the planetesimals away from its vicinity, which causes the planet and planetesimals to exchange energy and angular momentum and thus the planet migrates (Fernandez & Ip, 1984; Malhotra, 1993, 1995; Ida et al., 2000; Gomes et al., 2004; Kirsh et al., 2009).

For the planets in our solar system, numerical simulations (e.g. Fernandez & Ip, 1984; Hahn and Malhotra, 1999; Gomes et al., 2004) show that Jupiter migrates inwards, while Saturn, Uranus and Neptune migrate outwards. The orbital separation between each pair of planets increases with time. Over the dynamical lifetime of each particle, each planet suffers a small change in its orbital semi major axis, δa, which is different from planet to planet. Numerical simulations of the Centaur population[1] show that said population decays roughly exponentially with a certain e-folding time, τ_C (e.g. DiSisto & Brunini, 2007). Thus the radial displacement of the planets

[1]The Centaurs are the population of objects that are currently crossing the orbits of the giant planets; this population can be considered as a proxy for the primordial population of planetesimals that drove planet migration

must also decay exponentially, with the same τ:

$$a(t) = a_{\rm now} - \Delta a \, \exp(-t/\tau_C). \quad (3)$$

Here $a(t)$ is the semi major axis of each planet as a function of time, $a_{\rm now}$ the semi major axis of the planet at the end of migration (i.e. the current semi major axis) and Δa the total radial distance that the planet migrates.

Strictly speaking, the identity between the planet migration timescale τ and the planetesimals lifetime τ_C is valid only in case of *damped migration* (Gomes et al., 2004). In damped migration, the loss of planetesimals is not compensated by the acquisition of new planetesimals into the planet-scattering region that is due to the displacement of the planet itself. Thus, planet migration slows down progressively as planetesimals are depleted. In massive planetesimals disks, planet migration can be *self-sustained* (Ida et al., 2000; Gomes et al., 2004). In this case a planet can migrate through the disk by scattering planetesimals and leaving them "behind" relative to its migration direction. In this case, the migration speed does not slow down with time: it actually accelerates (until some saturation or migration reversal point is hit). So, obviously, a formula like (3) does not apply. Gomes et al. (2004) made a convincing case that self-sustained migration can not have occurred in the solar system. Even if it had occurred, though, it would have concerned only Neptune and Uranus. Jupiter and Saturn, given their large masses, always have damped migration (unless one considers planetesimals disks of unrealistic large masses, well exceeding the total mass of the gas giant planets). Thus, for Jupiter and Saturn, we can assume with confidence that their migration followed eq.(3). Thus, their orbital separation had to evolve as in eq. (2), with $\tau = \tau_C$.

The parameter Δa in (3) (or Δ_0 in eq. 2) is related to the total amount of mass of the planetesimals that drive the planet migration. Thus, increasing the mass of the planetesimal disk increases both the migration range (Δa) and the migration speed ($da/dt = \Delta a[\exp(-t/\tau_C)]/\tau_C$). However, when the planet is on an orbit with a given semi major axis $\bar{a}$, its migration rate is $da/dt(\bar{a}) = (a_{\rm now} - \bar{a})/\tau_C$, i.e. it is *independent* of Δa; therefore it is *independent* of the mass of the planetesimal disk: it depends only on τ_C.

Obviously, the same is true for the speed of migration of a resonance through a given location. A given location of a resonance corresponds to a given semi major axis $\bar{a}$ of a planet. Thus, the speed at which a resonance passes through the considered location, which in turns determines its effects, depends solely on the migration rate of the planet at $\bar{a}$ which, as we have just seen, depends only on τ_C and not on the mass of the planetesimal disk. We are lucky that this is the case because τ_C is pretty well constrained by simulations, whereas the total mass of the planetesimal disk is open to speculation.

The value of τ_C for Centaurs found in the literature ranges from 6 My for objects the Jupiter-Saturn region (Bailey & Malhotra, 2009) to 72 My in the Uranus-Neptune region (DiSisto & Brunini, 2007). Thus, we do not expect that planetesimal-driven migration of the giant planets can occur with a value of τ significantly shorter than ∼6 My. Indeed, a literature search for self-consistent simulations of planetesimal-driven migration yields a typical time scale $\tau \sim 10$ My (Hahn & Malhotra, 1999; Gomes et al., 2004).

By assuming that the orbital separation of Jupiter and Saturn evolved as in eq. (2), Minton &

Malhotra (2009) adopted a functional form that is appropriate for planetesimal-driven migration. However, the value of τ that they assumed (0.5 My), is not. The relevant τ (i.e. τ_C) is 10–20 times longer. For this reason, below we repeat the calculation of Minton & Malhotra (2009) using $\tau \sim 5$ My.

3. Planetesimal-driven migration and the asteroid belt

In this section we discuss the effects of planetesimal-driven migration of the giant planets on the asteroid belt. Our goal is to understand whether this kind of migration could have left the asteroid belt with an orbital structure compatible with the current one, for a reasonable set of initial conditions of the asteroids.

In Fig. 1 we present the current orbital structure of the asteroid belt with asteroids brighter than absolute magnitude $H = 9.7$ i.e. with diameter larger than $D \sim 50$ km. The orbital distribution of these large asteroids is not affected by observational biases (Jedicke et al., 2002) nor could it have been significantly modified over aeons by non-gravitational forces or family formation events. Therefore, these asteroids represent the belt's orbital distribution since the time when the migration of the giant planets ceased.

All the observed gaps correspond to the *current* locations of the main mean-motion resonances with Jupiter and of the ν_6 (i.e. $g = g_6$) secular resonance. These mean-motion resonances and the ν_6 secular resonance can remove asteroids from the belt because they increase their eccentricities and the asteroids become planet crossing. Therefore, it is not surprising that

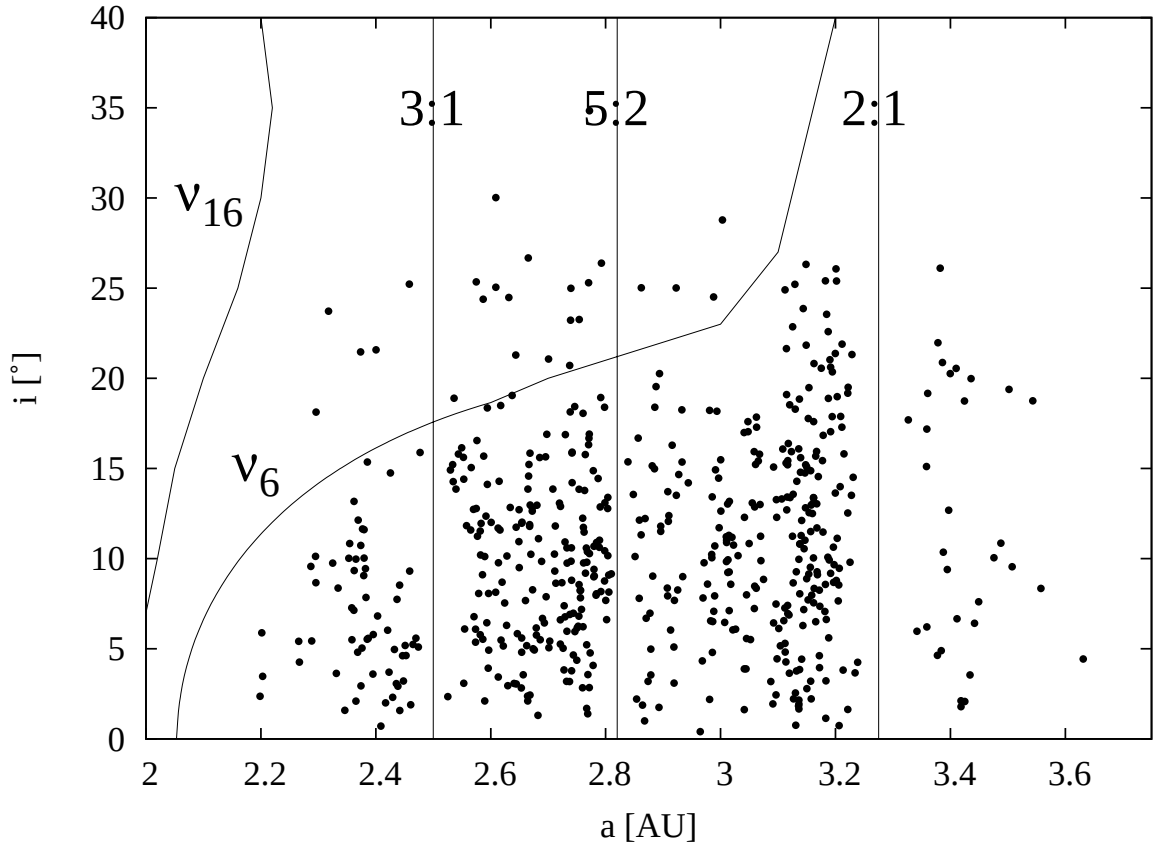

Fig. 1.— Current orbital distribution (inclination vs. semi major axis) of the asteroid belt. Only asteroids with absolute magnitude $H < 9.7$ are plotted (corresponding to a diameter of approximately 50 km). The locations of the $g = g_6$ (labelled ν_6) and $s = s_g$ (ν_{16}) secular resonances and of some of the major mean-motion resonances with Jupiter (labelled $n : m$, standing for the ratio between the orbital period of Jupiter and of an asteroid) are also plotted.

gaps in the asteroid distribution are visible around the current locations of these resonances. On the other hand, the ν_{16} (i.e. $s = s_6$) secular resonance produces large changes in the asteroids' inclination.

As the giant planets migrated, the mean motion resonances with Jupiter must have moved sun-ward towards their current positions. According to most accepted models the radial migration of Jupiter is expected to have covered 0.2-0.3 AU; thus the mean motion resonances should have moved inwards by approximately 0.1 AU. The ν_6 and ν_{16} secular resonances also moved sun-ward but their range of migration was much larger than that of the mean motion resonances. In fact, if the orbital separation of Jupiter and Saturn increased by more than $\Delta_0 = 1$ AU (again, as predicted by all models), the ν_6 resonance swept the entire asteroid belt as it moved inwards from 4.5 AU to 2 AU. The ν_{16} resonance swept the belt inside of 2.8 AU (Gomes et al., 1997) to its current location at 1.9 AU.

We now determine the effect of planet migration on the orbital distribution of the asteroid belt. We performed a sequence of numerical simulations, using the swift-WHM integrator (Levison & Duncan, 1994; Wisdom & Holman, 1991), as we explain here. We proceeded in three steps. In the first step, the code was modified to force the migration of Jupiter and Saturn as outlined in Paper I: the equations of motion were changed as to induce radial migration of the planets, with a rate decaying as $\exp(-t/\tau)$. For the reasons explained in the previous section, the value of τ was set equal to 5 My, the lower bound for τ_C.

Since the secular resonances only sweep the asteroid belt once the period ratio between Saturn and Jupiter $P_S/P_J > 2$ (Gomes, 1997) the planets were started on orbits with a period ratio of $P_S/P_J = 2.03$: Jupiter started at 5.40 AU and Saturn at 8.67 AU, similar to Malhotra (1993) and Minton & Malhotra (2009). The initial eccentricities and inclinations of the giant planets with respect to the invariable plane are close to their current values (Paper I): $(e_J, e_S) = (0.012, 0.035)$ and $(i_J, i_S) = (0.23°, 1.19°)$, and so the strength of the secular resonances passing through the asteroid belt does not change significantly throughout the migration. No eccentricity damping was imposed on the giant planets. The terrestrial planets were not included in this simulation, and neither were Uranus and Neptune. This simulation covered a time-span of 25 My, i.e. 5 times the value of τ.

The primordial asteroid belt was situated between 1.8 AU and 4.5 AU with orbits that did not cross those of Mars nor Jupiter. The initial orbits of the asteroids were generated according to the following recipe: take two random numbers and assign them to the pericenter and apocenter distances on the interval $[1.8, 4.5]$ AU. Then the eccentricity and semi major axis of the asteroids are $a \in (1.8, 4.5)$ AU and $e \in (0, 0.428)$. For the sake of simplicity the inclination was chosen at random between 0 and 20° while the three other angles were also chosen at random between 0 and 360°. Even though this method does not yield a uniform distribution in semi major axis and eccentricity, it turns out that this does not matter for the end result. A total of 10 000 asteroids were used per simulation. We ran eight simulations altogether with different choices of random numbers in the generation of the initial conditions, for a total of 80 000 test particles. Asteroids were removed if their distance to the Sun decreased below

1 AU (because in reality they would be rapidly removed by encounters with the Earth[2]), when they entered the Hill sphere of Jupiter, or they reached a distance further than 200 AU from the Sun.

After this simulation, we would like to continue the simulation including the effects of the terrestrial planets to account for the long-term modifications that these planets might have imposed to the asteroid belt orbital structure. Unfortunately this is not possible in a trivial way, because the final orbits of Jupiter and Saturn at the end of step 1 are not identical to the current orbits: the angular phases, for instance, are different. Thus, one cannot introduce other planets in the system, because the overall orbital evolution would then be different from the real dynamics of the solar system. Thus, we need to do first a simulation (step 2), where we bring Jupiter and Saturn to their exact current orbits, while integrating the dynamical evolution of the asteroids that survived at the end of step 1. This was done by forcing the semi major axes, eccentricities and inclinations of Jupiter and Saturn to linearly evolve from the values at the end of step 1 to their current values, in 5 My; the same was done for the angular elements, assuming frequencies that were as close as possible to the current proper frequencies so that they performed the correct number of revolutions. The long time scale of 5 My allowed the asteroids to adapt in an adiabatic fashion to the new, slightly different configuration of the giant planets.

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[2]We decided not to put a limit at 1.5 AU, corresponding to Mars-crossing orbits, because the time scale for Mars encounters to change significantly the asteroid's orbit is ~100 My. Thus, in principle, asteroids could become temporary Mars-crosser and then go back into the main asteroid belt.

At this point we could add the remaining planets to the system (the terrestrial planets and Uranus and Neptune), assuming their current orbital configuration. The third step of our study consisted in following the asteroids for another 400 My under the influence of all the planets. Now, asteroids were removed when they entered the Hill sphere of any planet.

The final distribution of the asteroids at the end of these 3 steps is depicted in Fig. 2. It is clear that this distribution is vastly different from Fig. 1. The most striking difference is that the ratio $\mathcal{R}$ between the number of asteroids with inclinations above (denoted high-i) and below (low-i) the ν_6 resonance in the region of the asteroid belt interior to 2.8 AU is much higher in Fig. 2 (0.7) than in Fig. 1 (0.07). This ratio, at the beginning of the simulation, was 0.08.

It is well-known that the effects of secular resonances on the orbital distribution of the asteroids is anti-correlated with the speed at which these resonances sweep through the asteroid belt (Nagasawa et al., 2000). Thus, we believe $\mathcal{R}$ to be an important diagnostic of the rate of planet migration. If the planets migrate slowly, as in our simulation (τ = 5 My), the ν_{16} pushes asteroids to high inclinations while the ν_6 resonance is effective at removing the low-inclination asteroids. This results in a high $\mathcal{R}$. Planet migrations with $\tau > 5$ *My* would give final distributions that are likely even more different from the current belt than that presented in Fig. 2: the value of $\mathcal{R}$ would be either more extreme or similar to what is presented here. In Minton & Malhotra (2009) the planets were assumed to migrate so fast (τ = 0.5 My) that the secular resonances swept the asteroid belt so quickly that they did not have time to act; thus, the final value of $\mathcal{R}$ was similar to the initial one.

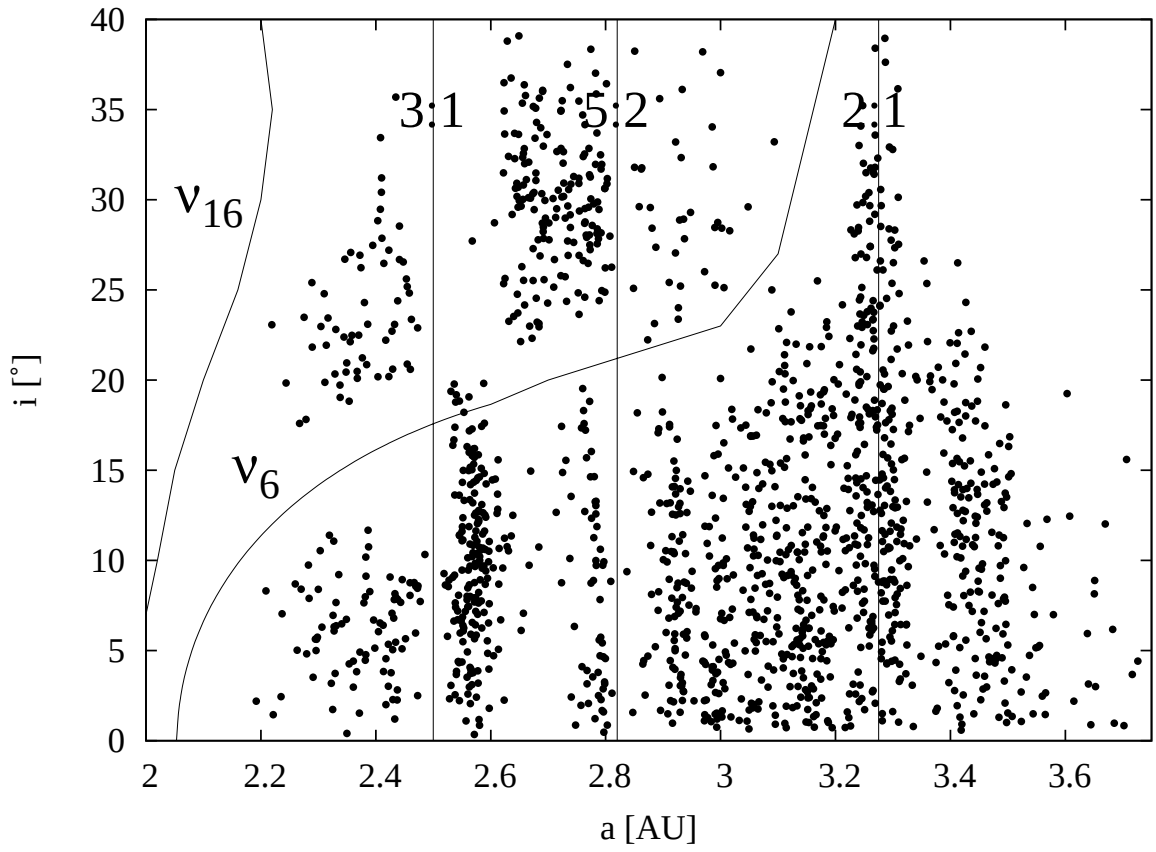

Fig. 2.— Orbital distribution of the asteroid belt at the end of the three step-wise simulations described in the main text. The first of these simulations enacted planetesimal-driven migration of Jupiter and Saturn with a timescale $\tau = 5$ My.

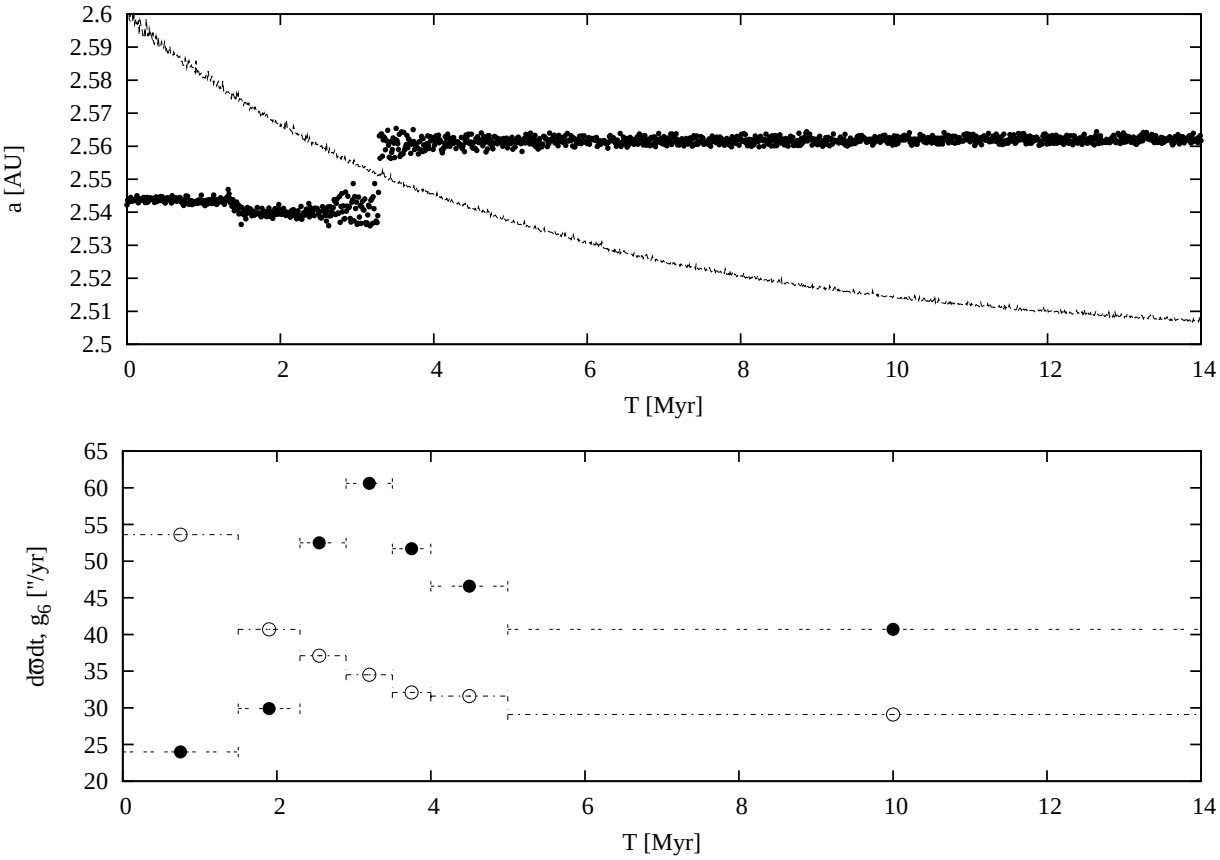

Fig. 3.— Example of an asteroid jumping across the 3:1 resonance with Jupiter. The top panel depicts the semi major axis of the asteroid (bullets) and the location of the 3:1 resonance with Jupiter (solid line) as a function of time. The bottom panel shows the proper precession frequency $\dot{\varpi} \equiv g$ of the asteroid (filled circles), and g_6 (open circles) as a function of time. The values are averages over the interval traced by the horizontal error bars.

The other two characteristic features of Fig. 2 that are very different from the real asteroid distribution are (i) the appearance of a dense group of objects at 2.55 AU, next to the current location of the 3:1 resonance with Jupiter at 2.50 AU, and (ii) a prominent lack of objects in the 2.6–2.7 AU range with inclinations below the ν_6 resonance. The latter is caused by the sweeping of ν_6, which moves the asteroids to orbits with Earth-crossing eccentricities, where they are removed. The clump next to the 3:1 resonance is formed by asteroids jumping across this resonance as the latter moves sun-ward. An example of this event is depicted in Fig. 3. The top panel shows the semi major axis of an asteroid (bullets) and the location of the 3:1 resonance with Jupiter (solid line). One can clearly see the jump in semi major axis as the asteroid encounters the resonance. Notice that the asteroid is not captured in the resonance, but jumps from its inner side to the outer side. The bottom panel of Fig. 3 shows (filled circles) the average rate of the precession of the asteroid's longitude of pericenter, g, over the time interval traced by the horizontal error bars. As one can see, g increases dramatically, by almost a factor of 2, while the asteroid jumps across the resonance (Knezevic et al., 1991). At the same time g_6 decreases smoothly and monotonically (open circles). Thus, the asteroid crosses the $g = g_6$ resonance extremely fast. This is not because g_6 decreases fast (as in Minton and Malhtora, 2009), but because g increases very fast. The result is that, for asteroids jumping across the 3:1 resonance, the $g = g_6$ secular resonance sweeping is too fast to be effective, and therefore these asteroids can survive on a moderate eccentricity orbit until the end of the simulation.

All the results illustrated above strongly argue that the current structure of the asteroid belt is incompatible with a smooth migration of the giant planets with $\tau \sim 5$ My. As this is the minimal time scale for planetesimal-driven migration, this excludes that the orbital separation between

Jupiter and Saturn increased due to the sole process of planetesimal scattering. We think that there is no easy way around this result for the following reasons:

- As explained above, larger values of τ beyond 5 My, the only possible ones in planetesimal-driven migration, would not improve the final value of $\mathcal{R}$.

- The original inclination distribution inside 2.8 AU is not important for the final result because it is mixed by the sweeping of the ν_{16} resonance; the inclinations are dispersed over the interval from 0 to 30°, whatever their initial distribution, and thus the value of $\mathcal{R}$ is always nearly the same. Figure 4 proves this claim. Here we show the result of a smooth, planetesimal-driven migration simulation with $\tau = 5$ My on an asteroid belt with an initially uniform inclination distribution up to 10° only. All other initial conditions are the same as in the simulations discussed before. A visual comparison with the current distribution in the asteroid belt (Fig. 1) clearly shows that there are still too many asteroids with semi major axes $a < 2.8$ AU above the ν_6 resonance. In fact, for this simulation $\mathcal{R} = 0.6$, only slightly lower than in the original simulation of Fig. 2 (0.7), but still an order of magnitude higher than the observed ratio (0.07). Thus, as we claimed above, inside 2.8 AU the initial inclination distribution does not matter for the final result. Conversely, for $a > 2.8$ AU, the asteroid belt preserves the initial inclination distribution because it is not swept by the ν_{16} resonance. Consequently, we see in Fig. 4 that there is a strong deficit of bodies with inclinations $i > 10°$ beyond 2.8 AU, with the exception of the neighborhood of the 2:1 mean-motion resonance with Jupiter (at 3.2 AU). As one can see, this distribution does not match the observations either: a broader initial inclination distribution would be required.

- All models agree that the separation between Jupiter and Saturn increased by at least 1 AU, but it could have been more. Increasing the distance travelled by Jupiter and Saturn would result in practically the same dynamics because of two reasons: First, the asteroid belt is only affected by secular resonances when $P_S/P_J > 2$ (Gomes, 1997) i.e. towards the end of migration (Malhotra, 1993; Tsiganis et al., 2005; Gomes et al., 2005). Hence, any prior migration of the giant planets plays no role in shaping the belt. Second, as we said in sect. 2, the rate of migration of the resonances at a given location (say in the inner asteroid belt) depends only on τ and is independent of the range of migration that the planets travelled overall.

- In principle one could envision that the eccentricities and/or inclinations of Jupiter and Saturn were smaller than their current values for most of the migration, thereby weakening the effects of the secular resonances. However, this is unlikely because we are not aware of any mechanism that is able to excite the eccentricities or inclinations of the giant planets towards the end of the migration (Paper I).

- The radial migration of the giant planets is believed to be the last major event that sculpted the structure of the Solar System, which coincided with the Late Heavy Bombardment (LHB) of the terrestrial planets (Levison et al., 2001; Gomes et al., 2005; Strom et al., 2005). Thus, we do not foresee any plausible mechanism capable of subsequently erasing the signature of resonance sweeping in the asteroid belt, particularly of decreasing $\mathcal{R}$ by an

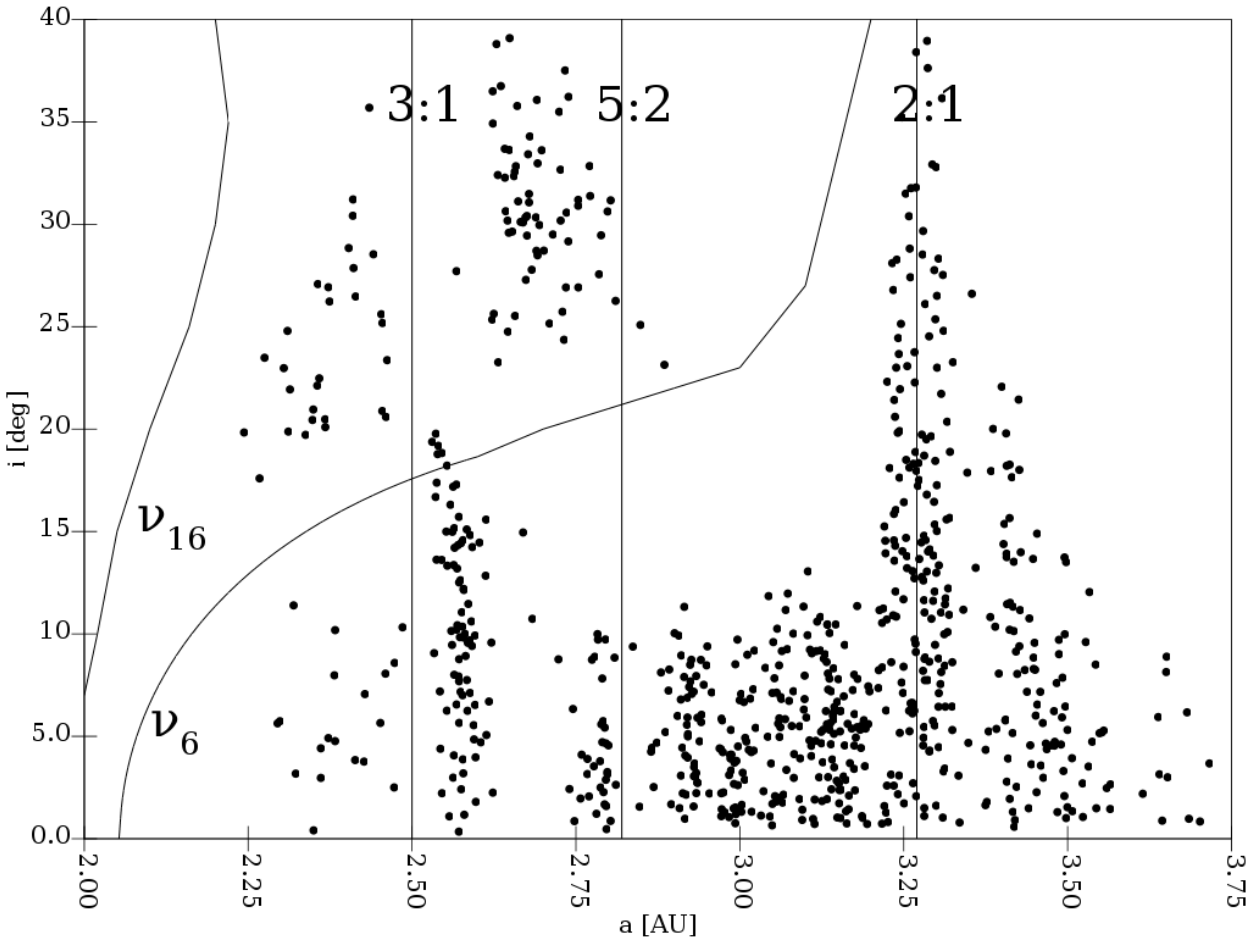

Fig. 4.— Orbital distribution of the asteroid belt after smooth migration of Jupiter and Saturn with $\tau = 5$ My, assuming the belt had an original uniform inclination distribution up to 10°.

order of magnitude.

For all these reasons, we conclude that planetesimal-driven migration could not have dominated the radial displacement of Jupiter and Saturn. Thus below we look for an alternative mechanism that results in a migration that is faster than the planetesimal-driven one and hence is consistent with the short time scale used by Minton & Malhotra (2009).

4. A jumping-Jupiter scenario

Encounters between the giant planets, besides planetesimal scattering, is the only mechanism that is known to us to be able to produce large-scale orbital separation of the planets. However, planetary encounters do not necessarily help our case of speeding up the divergent migration between Jupiter and Saturn. For example, if Saturn scatters an ice giant (Uranus or Neptune) outwards, it has to recoil towards the Sun due to energy conservation. If Jupiter does not encounter any planet, the orbital separation between Jupiter and Saturn *decreases* and planetesimal-driven migration is still required to bring the planets to their current orbital separation. This would lead to the same problems with the asteroid belt as discussed above. Thus, such a series of events has to be rejected. However, if an ice giant is first scattered inwards by Saturn and subsequently outwards by Jupiter, then the orbital separation between Jupiter and Saturn increases abruptly. As in paper II, we call this a ‘jumping-Jupiter evolution’, in which the orbital separation between Jupiter and Saturn increases on a time scale of 10 000–100 000 years, even shorter than assumed in Minton & Malhotra (2009). However, the motion does not follow a smooth, exponential form. In the Nice model (Tsiganis et al., 2005; Gomes et al., 2005) a ‘successful’ jumping-Jupiter evolution, i.e. one where Uranus and Neptune end on orbits with semi major axes within 20% of

their current values, occurs in ~ 10% of our simulations (Paper II).

We stress that, at least in the Nice model, there is no appreciable difference in the initial conditions of the jumping-Jupiter evolutions with respect to those which lead to Jupiter not being involved in encounters. This is because of the chaotic nature of the dynamics, due to which both types of evolutions can originate from practically the same simulation setup.

An example of a jumping-Jupiter evolution is shown in Fig. 5 and was taken from Paper II. The black and grey curves show the evolution of the semi major axes of Jupiter and Saturn (top panel), and their eccentricities (bottom panel), reported on the left-side and right-side vertical scales, respectively. The stochastic behavior is caused by repeated encounters with a Uranus/Neptune-mass planet (not shown here) which was originally placed the third in order of increasing distance from the Sun. Time $t = 0$ is arbitrary and corresponds to the onset of the phase of planetary instability. The full evolution of the planets lasts 4.6 My and all giant planets survived on stable orbits that are quite similar to those of the real planets of the Solar System. The final ratio of the orbital periods of Saturn and Jupiter is 2.45, very close to the current value.

5. Evolution of the asteroid belt during a jumping-Jupiter evolution

In this section, we present results of the distribution of the asteroid belt following the jumping-Jupiter scenario of Fig. 5. Once again we employ three distinct steps, in the same manner as described in sect. 3 for the smooth migration. The only difference is that for the first step we

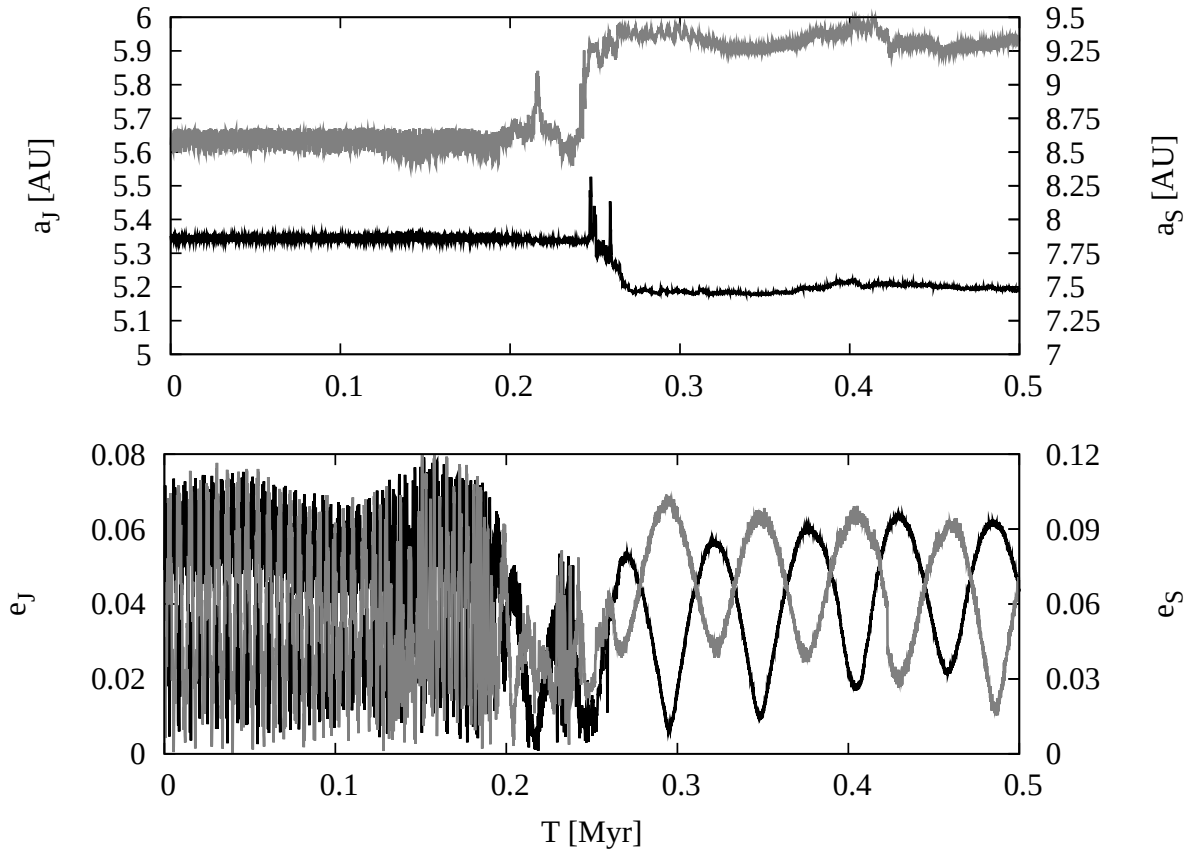

Fig. 5.— Example of a jumping-Jupiter evolution. The top panel depicts the semi major axes of Jupiter (black) and Saturn (grey) – reported on the left and right sides respectively – during the first 0.5 My of the simulation. Their eccentricities are plotted in the bottom panel.

enact the jumping-Jupiter evolution rather than adopting a smooth, exponential migration. We used the same initial conditions for the asteroids as those adopted for the smooth migration case of Fig. 2 and enacted the jumping-Jupiter evolution using the modified version of swift-WHM, presented and tested in Paper II. In this code, the positions of Jupiter and Saturn have been computed by interpolation from the 100 yr-resolved output of the evolution shown in Fig. 5. We eliminated the asteroids that collided with the Sun (perihelion distance smaller than the solar radius) or were scattered beyond 200 AU. The terrestrial planets were not included.

After the jumping-Jupiter evolution, we performed the second step in the same manner as described in sect. 3, during which Jupiter and Saturn are smoothly brought to their exact current orbits. Finally, for the third step, the terrestrial planets and Uranus and Neptune were added to the system on their current orbits and with the correct phases, and the evolution of this system was simulated for another 3.3 Gy.

The orbital distribution of the asteroid belt at the end of the third step is shown in Fig. 6. It is remarkably similar to the current one depicted in Fig. 1, with no spurious gaps and clumps, unlike Fig. 2. The final value of $\mathcal{R}$ is identical to the observed value. However, unlike the smooth and slow migration case, $\mathcal{R}$ now depends on the assumed initial inclination distribution of the asteroids (here uniform up to 20°). This is because the ν_{16} resonance sweeps the belt so fast that it does not significantly modify the inclinations of the asteroids, as explained in sect. 3.

To illuminate this fact, in the framework of the same jumping-Jupiter evolution, we simulated

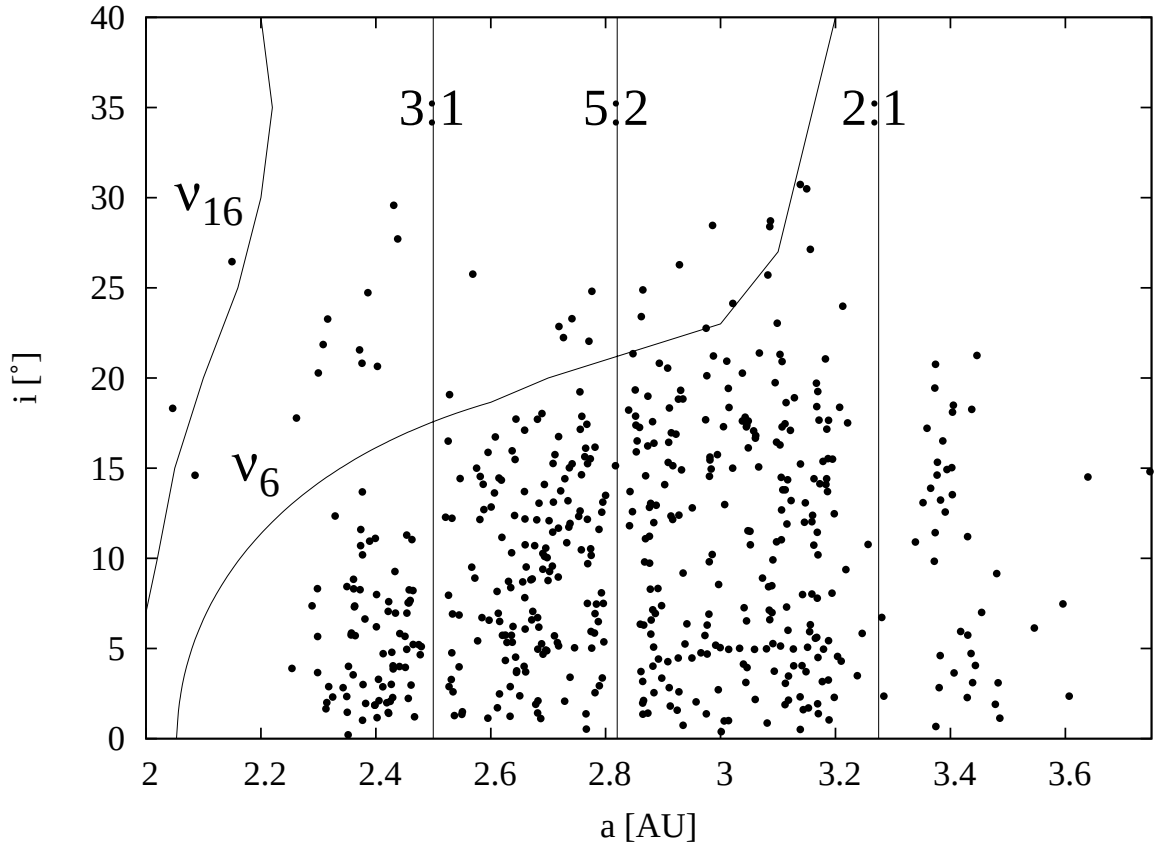

Fig. 6.— The orbital distribution of the asteroid belt 3.3 Gy after the end of the jumping-Jupiter evolution.

the evolution of asteroids that are subject to the effects of sweeping by the ν_{16} resonance, i.e. asteroids with $a < 2.8$ AU, but with inclinations up to 40°. At the end of this simulation, the root-mean-square change in inclination of the asteroids was only 4°, so that the original inclination distribution is approximately preserved. Therefore, the jumping-Jupiter scenario is consistent with the asteroid belt, provided that the pre-migration asteroid distribution was similar to the current inclination distribution of large asteroids, i.e. relatively uniform in inclination, up to about 20°. An orbital excitation of the asteroid belt pre-dating the jumping-Jupiter evolution is likely. In fact, it is generally expected the asteroid belt lost its original state of a dynamically cold disk during the phase of terrestrial planets formation (Wetherill, 1992; Chambers and Wetherill, 1998; Petit et al., 2001; O'Brien et al., 2006, 2007). This happened much earlier than the instability of the giant planets if the latter occurred at the LHB time (see Appendix).

As we said above, we are not aware of a third way that, after the disappearance of the gas–disk, could widen the orbital separation between Jupiter and Saturn, other than planetesimal-driven migration and a jumping-Jupiter evolution. We have shown in sect. 3 that the former produces results inconsistent with the structure of the asteroid belt, whatever its initial orbital distribution. On the other hand, the jumping-Jupiter mechanism can work, provided that the asteroid belt had the appropriate distribution, that is an inclination distribution up to $\sim 20°$, which is not unreasonable. Thus, our conclusion is that the actual evolution of the giant planets of the solar system was of the jumping-Jupiter type. This conclusion has a long list of implications, which we discuss in the next section.

6. Implications

6.1. Capture of the Irregular satellites of Jupiter

Nesvorný et al. (2007) showed that the capture of irregular satellites is a generic outcome of planet-planet encounters and reproduces their orbital distribution well. They showed that this capture mechanism also works for Jupiter provided that it participates in the encounters, which we support here. Bottke et al. (2010) showed that the size distribution of the irregular satellite systems is also consistent with this scenario.

6.2. Contribution of main belt asteroids to the LHB

To evaluate which fraction of the asteroid belt population becomes unstable during the jumping-Jupiter evolution and what is the subsequent overall asteroidal impact flux onto the Earth and the Moon, we have proceeded with the same sequence of piece-wise simulations similar to what was described in Sections 3 and 5, but we added another step (step 0) prior to re-enacting the jumping-Jupiter scenario (which is step 1).

For step 0 we started with the same uniform distribution of asteroids as described in sect. 2. We assumed that the giant planets are situated on the orbits described in Morbidelli et al. (2007). These orbits are fully resonant, quasi-circular and co-planar. Jupiter and Saturn are locked in their mutual 3:2 mean motion resonance; Uranus is in the 3:2 exterior mean motion resonance with Saturn and Neptune is in the exterior 4:3 mean motion resonance with Uranus. These orbits are the result of hydro-dynamical simulations of the dynamical evolution of the giant planets embedded in

a gas disk. This configuration is stable after the dispersal of the gas nebula in absence of an exterior planetesimal disk, and are thus believed to be the orbits the giant planets had in the interim between the end of the gas disk phase and the onset of their global dynamical instability. If one believes this instability triggered the LHB, this compact configuration had to last for approximately 600 My.

To set up the right initial conditions for determining the amount of mass transferred to the Moon, we have integrated the asteroids under the influence of the giant planets on these presumed pre-LHB multi-resonant orbits for 600 My (step 0). The terrestrial planets were not included in this simulation. Asteroids were removed when their perihelion distance decreased below 1.5 AU i.e. when they became Mars-crossers, or had an encounter with Jupiter. A total of 724 out of the original 1 000 asteroids survived. The final orbital distribution in semi major axis-eccentricity space of the asteroids is shown in the top-left panel of Fig. 7. As one can clearly see, no gaps are visible near resonances with Jupiter. In fact, it is well known that mean motion resonances are stable if Jupiter follows a circular orbit (Morbidelli, 2002). This represents what we believe is a realistic orbital distribution of the asteroids at the onset of giant planet migration.

For step 1 (the second simulation), we integrated the remaining 724 particles while enacting the jumping-Jupiter evolution. The second step was identical to what has been described earlier, while for the third step the terrestrial planets, Uranus and Neptune were added and the system was simulated for another 25 My. In the last three steps asteroids were removed if they collided with the Sun, a planet or were scattered beyond Jupiter. At the end of the third step 319 out of 724 particles survived (45%). We expect that this number is close to the final number of surviving asteroids because only a few were still crossing the orbits of Mars and the Earth at the end of the

last step.

To compute the mass impacting the Moon and the Earth we proceeded as follows. During steps 1 and 2, we computed the collision probability of every particle with our planet and its satellite, assuming that the latter were on their current (fixed) orbits. We performed this calculation using the algorithm presented in Wetherhill (1967). During the last step, we used the same approach, but adopted the orbital values of the Earth obtained during the simulation itself. The Moon was assumed to be at the current distance from our planet.

We understand that this procedure is not ideal. The fact that there are no terrestrial planets in steps 1 and 2 probably increases the lifetime of some objects that escaped from the asteroid belt. Also, the strength of the ν_6 resonance is severely reduced during step 2 because the secular forcing between Jupiter and Saturn is not taken into account. This might also artificially enhance the lifetime of some of the destabilized asteroids. For these reasons, our results should be regarded as being upper bounds to the real flux of matter from the asteroid belt towards the Earth-Moon system.

We find that the mean collision probability of our initial 724 asteroids with the Moon during steps 1 to 3 is 4×10^{-5}. This number includes particles on stable orbits, so the mean collision probability of asteroids dislodged from the asteroid belt is about twice as much i.e. 8×10^{-5}. The collision probability with the Earth is 20 times larger. The mean impact velocity, before gravitational focusing, is 20 km/s.

To translate these collision probabilities into estimates of the total mass impacting the Earth-Moon system, we take into account that Minton & Malhotra (2010) argued that the asteroid belt might have lost half of its population during the last 3.5 Gy because of chaotic diffusion. The current mass of the asteroid belt is estimated to be 3.6×10^{21} kg (Krasinsky et al., 2002) or 6×10^{-4} Earth masses ($M_\oplus$). If the post-LHB mass was twice as much and $\sim$ 50% of the population was destabilized during the jumping-Jupiter evolution, then our 724 asteroids represent a total mass of $\sim 1.5\times10^{22}$ kg or 2.5×10^{-3} $M_\oplus$. Multiplying this by the mean collision probability with the Moon we find that a total of 6×10^{17} kg was delivered to our satellite during the LHB from within the current boundaries of the asteroid belt. The total mass delivered to the Earth is 20 times larger. This is about an order of magnitude smaller than the cometary contribution, as calculated in Gomes et al. (2005). The cometary flux is quite insensitive to the exact dynamics of the giant planets, because the orbital evolution of the comets is dominated by planetary scattering and not by resonance sweeping. Thus, unless the trans-Neptunian disk had a substantially lower mass than currently thought, we have little reason to believe that the estimates about the cometary flux in Gomes et al. (2005) need to be significantly revised in the framework of the jumping-Jupiter scenario. Consequently, we conclude that, if the original asteroid belt population was uniform in semi major axis, comets should have dominated the LHB over main belt asteroids.

This conclusion, however, might violate constraints. There is a lively debate on the nature of the LHB. It was argued (Kring & Cohen, 2002) that the basin-forming projectiles were neither comets nor primitive asteroids, in contrast with our result. If this is confirmed, it will be necessary to look for alternative sources of projectiles, such as putative populations of small bodies in between the orbits of the terrestrial planets, that could become fully destabilized during the

jumping-Jupiter evolution.

6.3. The pre-LHB structure of the asteroid belt

Since the jumping-Jupiter scenario preserves the original inclination distribution, and only ~ 50% of the main belt population is removed onto planet-crossing orbits, the asteroid belt had to be relatively similar to today's belt at the time when giant planet migration started i.e. at the time of the LHB, if one accepts that the two events are connected (Levison et al., 2001; Gomes et al., 2005; Strom et al., 2005). More precisely, the asteroid inclinations had to be spread between 0 and 20°, and the total mass of the belt had to be comparable to the current one. Thus, a very small number (if any) of bodies larger than Ceres (called planetary embryos) could exist. This provides a new set of formidable constraints for future models of the primordial dynamical excitation and depletion of the asteroid belt occurring during terrestrial planet formation (Wetherill, 1992; Petit et al., 2001; O'Brien et al., 2006, 2007).

6.4. Orbits of the giant planets before the onset of their dynamical instability

The fact that the asteroid belt roughly preserves its pre-LHB structure during a jumping-Jupiter evolution also provides constraints on the orbits that the planets had to have had prior to their migration. If the orbits of Jupiter and Saturn had had eccentricities comparable to their current values, gaps would have been carved within a few million years, exactly where the main resonances were located in the pre-migration phase, and they would still be visible today. This is demonstrated below.

Today, the eccentricity of Jupiter causes the main Jovian mean-motion resonances to be unstable: the eccentricities of resonant asteroids are increased to such large values that they begin to cross the orbits of the planets (Gladman et al., 1997). Some of these planet-crossing objects are removed from the resonances by encounters with these planets, while others have their eccentricities increased to Sun-grazing values. The removal of asteroids from these resonant locations is the reason for the 'gaps' that we see in the distribution of asteroids today (see Fig. 1).

The most powerful resonance with Jupiter is the 3:1 resonance, centered at 2.50 AU with a width of approximately 0.05 AU. If Jupiter had had an eccentricity similar to its current value before migration, when its semi major axis was about 5.4 AU, then a gap near 2.6 AU should have rapidly opened in the asteroid distribution, clearly distinct from the currently observed gap at 2.5 AU. In fact, after the migration of Jupiter the gap opened by the 3:1 resonance at its final location would probably overlap with the pre-migration gap, resulting in a wide empty zone ranging from approximately 2.45 to 2.65 AU

We tested this hypothesis by performing the following experiment. Jupiter and Saturn were placed on orbits similar to those described in Malhotra (1993, 1995) and Minton & Malhotra (2009): Jupiter was set at 5.4 AU and Saturn at 8.7 AU on orbits with their current eccentricities. There were no terrestrial planets. We considered a distribution of asteroids consisting of 2 000 test particles, with the same initial conditions as described in sect. 3. Assuming, as in Minton & Malhotra (2009) and Strom et al. (2005), that the trigger of giant planet migration was delayed by

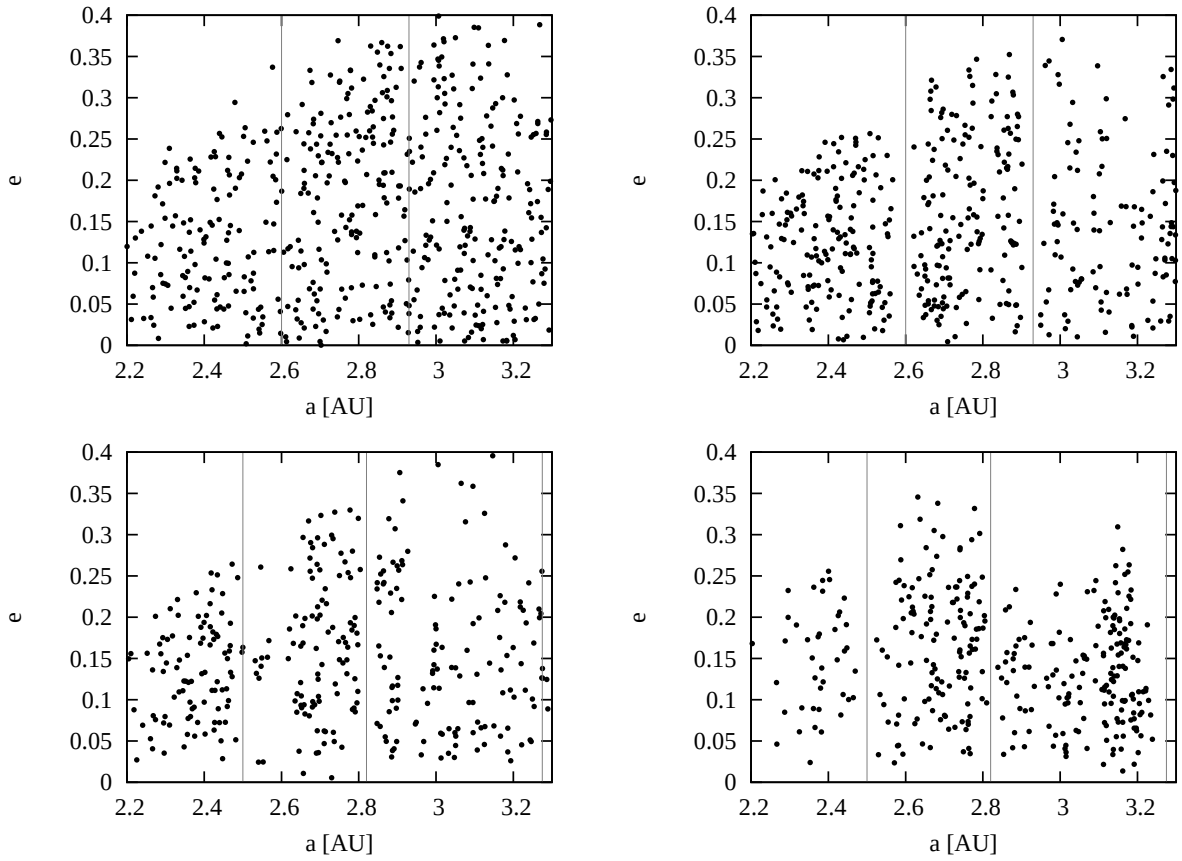

Fig. 7.— Semi major axis vs. eccentricity distribution of the asteroid belt for various configurations of the giant planets. The top-left illustrates the distribution after 600My of evolution with the giant planets on multi-resonant quasi-circular orbits of Morbidelli et al. (2007). The top-right panel shows the orbital distribution after 600 My of evolution, assuming that Jupiter and Saturn stayed on non-migrating orbits corresponding to the initial conditions of Minton & Malhotra (2009). The bottom-left panel illustrates how the distribution in the top-right panel would have evolved after a fast ($\tau = 0.1$ My) exponential migration of Jupiter and Saturn towards their current orbits, plus a 400 My subsequent integration. For reference, the bottom right panel shows the current distribution of 335 asteroids (same number as the particles plotted in the bottom-left panel), among the real $H < 9.7$ asteroid population.

$\sim$ 600 My, so that it coincides with the beginning of the LHB, we first simulated the evolution of these asteroids for 600 My, without imposing any migration on the giant planets. Once again asteroids were removed when their perihelion distance decreased below 1.5 AU or they encountered Jupiter. The asteroid distribution at the end of this simulation is depicted in the top-right panel of Fig. 7. The gap associated with the 3:1 resonance (located in this simulation at 2.6 AU) is clearly visible as well as that of the 5:2 resonance (currently at 2.82 AU but here at 2.93 AU). These 'fossil' gaps are not observed today (c.f. Fig. 1), so either they never formed or were refilled by some mechanism (see below).

We subsequently simulated the remaining asteroids, imposing a smooth exponential migration of the orbits of Jupiter and Saturn, but on a time scale $\tau = 0.1$ My. This choice of τ 'mimics' the fast migration time scale of the jumping-Jupiter scenario. After the migration was finished, the system was simulated for another 400 My without terrestrial planets, which is long enough for gaps to open near the final positions of the resonances. The resulting orbital distribution of the asteroid belt at this epoch is plotted in the bottom-left panel of Fig. 7. As expected, there is a very large depletion of objects between 2.5 and 2.6 AU, which is especially prominent at small eccentricities. A few objects remain in the middle of this wide gap, because they managed to jump across the sweeping 3:1 resonance. This wide gap is not observed in the asteroid belt today. In fact, the bottom-right panel of Fig. 7 shows, for comparison, the observed distribution of asteroids with absolute magnitude $H < 9.7$. For consistency, we have randomly selected a number of real asteroids equal to the number of particles (335) that remained until the end of the simulation, in the range of semi major axes shown here.

We conclude from this experiment that migration on a jumping-Jupiter time scale could not have replenished the fossil gaps opened by Jupiter if the latter had been originally situated on an orbit with eccentricity comparable to its current value.

We do not foresee any other mechanism that could replenish the fossil gaps for the following reasons. First, remember that the real asteroids that we are considering as tracers of the asteroid belt are big (larger than approximately 50 km). These objects are too large to migrate under the Yarkovsky effect. Additionally, only a few of them are members of a collisional family. Thus, neither non-gravitational forces, nor collisional breakups could have refilled the pre-migration gaps with such large objects (the same is not true, obviously, for smaller objects, for which we would not expect to see any fossil traces of the pre-migration gaps). Thus, the only remaining possibility is that massive bodies (hereafter called planetary embryos) resided in the belt and displaced the asteroids by gravitational scattering. As we said above, it is unlikely that bodies more massive than Ceres existed in the belt up to the time of giant planet migration. But even if some embryo had been in the belt, it is unlikely that it could have refill the gaps. In fact, from our first simulation, where Jupiter and Saturn are at 5.4 AU and 8.7 AU with their current eccentricities, we found that the mean lifetime of particles with semi major axes in the range 2.57–2.61 AU (i.e. in the region of the gap opened by the 3:1 resonance in the pre-migration phase) is 6 My. This region is 25 times narrower (0.04 AU) than the whole belt (1 AU). Thus, to prevent a gap from opening, embryos should have been injecting 1/25 of all asteroids in this resonance every 6 My. Assuming that the pre-migration phase lasted 600 My, the equivalent of 4 asteroid belts should have been injected into the 3:1 resonance, to be subsequently removed by its action. We strongly doubt that any planetary embryo could have done this without leaving other

scars in the asteroid belt distribution, even more pronounced than the fossil gaps themselves!

In conclusion, given that fossil gaps could not be replenished and they are not observed today, we believe that it is unlikely that they ever existed. This implies that the giant planets had to reside on quasi-circular orbits before the LHB, in accordance with the hydro-dynamical simulations of Morbidelli et al. (2007) (c.f. the top-left panel of Fig. 7).

7. Conclusions

Minton & Malhotra (2009) showed that the current orbital structure of the asteroid belt is consistent with a primordial uniform distribution of asteroids in semi major axis, eccentricity and inclination space, and an exponential migration of the giant planets with a characteristic time scale $\tau = 0.5$ My. However, they did not demonstrate that τ needs to be this short, nor they discussed by which mechanism planet migration could operate on this timescale.

In this paper we have demonstrated that the migration of the giant planets, with $\tau = 5$ My or longer, is inconsistent with the current structure of the belt, whatever its initial orbital distribution. The divergent migration of Jupiter and Saturn needs to be as fast as used in Minton & Malhotra, or even faster.

This constraint on the time scale of migration unveils the dominant process by which the

orbits of Jupiter and Saturn separated from each other. In principle, two mechanisms are possible: (i) planetesimal driven migration or (ii) encounters of both Jupiter and Saturn with a third planet (presumably Uranus or Neptune). The first mechanism results in an exponential migration, but the characteristic τ cannot be faster than 5 My. Given the incompatibility of this value of τ with the current structure of the asteroid belt, this process can be excluded. The second mechanism, dubbed 'jumping-Jupiter evolution', results in a radial displacement of the orbits of Jupiter and Saturn on a time scale shorter than 0.1 My, but the migration of the planets cannot be well represented by an exponential law. We have simulated the evolution of the asteroid belt during a jumping-Jupiter evolution and we have found that the final orbital structure of the belt matches well the observed one, provided that the original belt had an approximately uniform inclination distribution that extended up to $\sim 20^{\circ}$.

This result strongly argues that the real evolution of the giant planets was of the jumping-Jupiter type and that the orbits of the giant planets, before migration, were significantly more circular than the current ones.

8. Appendix: A temptative timeline of events characterising the Solar System evolution, as emerging from this and previous works.

The first solids of the solar system condensed 4.568 Gy ago (see Kleine et al., 2009 for a review). This is generally considered as *time zero* in solar system history.

Because most of the mass of Jupiter and Saturn is in H and He, these planets must

have formed in a quite massive gaseous proto-planetary disk (Pollack et al., 1996). Because proto-planetary disks typically last 3-5 My around young stars (Haisch et al., 2001), Jupiter and Saturn should have formed within this time.

When embedded in a gas disk, giant planets tend to migrate towards the central star (Lin and Papaloizou, 1986). Hydro-dynamical simulations (Masset and Snellgrove, 2001; Morbidelli and Crida, 2007; Pierens and Nelson, 2008) have consistently shown that Saturn migrates faster than Jupiter and, as it approaches the latter, it is eventually captured in their mutual 2:3 mean motion resonance. At this point, the inward migration of the two planets stops. Depending on the disk parameters, the two planets either stay in place, or migrate outward in resonance, until the disappearance of the disk (Morbidelli and Crida, 2007). This explains why we do not have a hot Jupiter in our Solar System. Walsh et al. (2010) proposed that Jupiter migrated down to 1.5 AU before Saturn formed and was captured in resonance; when this occurred, the two planets reversed migration and Jupiter reached 5.4 AU when the gas-disk disappeared. Either way (i.e with or without a substantial outward migration of Jupiter and Saturn), when the gas disk disappeared around 3–5 My, Jupiter and Saturn should have been in their mutual 2:3 mean motion resonance, with quasi circular and co-planar orbits, with Jupiter at about 5.4 AU. Uranus and Neptune, should also have been in resonances with Saturn and with themselves, trapped in this configuration by differential migration during the gas-disk phase: however, there are multiple resonances in which these planets might have been (Morbidelli et al., 2007; Batygin and Brown, 2010).

At the disappearance of the gas, two massive disks of planetesimals should have remained: one in the inner solar system, with an outer edge located close to the minimal orbital radius that Jupiter acquired during its evolution in the gas-disk, and one in the outer solar system, beyond the orbit of the most distant planet. The terrestrial planets formed by mutual collisions from the inner

disk. Geochemical constraints (Touboul et al., 2007; Allegre et al., 2008; Kleine et al., 2009) and numerical modeling (Chambers and Wetherill, 1998; Chambers, 2001; Raymond et al., 2006; O'Brien et al., 2006; Hansen, 2009; Morishima et al., 2010) suggest that the terrestrial planets took 30–100 My to form.

By the time terrestrial planet formation was completed, the asteroid belt was substantially depleted and dynamically excited. If Jupiter never went significantly inwards of 4–5 AU, the depletion and dynamical excitation of the asteroid belt occurred during the terrestrial planets formation process, due to the combination of perturbations from resident planetary embryos and Jupiter (Wetherill, 1992; Chambers and Wetherill, 1998; Petit et al., 2001; Raymond et al., 2006; O'Brien et al., 2006, 2007). In the Walsh et al. (2010) scenario, the asteroid population had already been depleted and excited by the inward and outward migration of Jupiter through the main belt region during the gas-disk phase. The orbital excitation of the asteroid belt at $t \sim 100$ My is model dependent. For instance, in Petit et al. (2001) the final inclinations of the surviving asteroids were within 15 degrees; in O'Brien et al. (2006) most of the surviving asteroids had $10^\circ < i < 30^\circ$; in Walsh et al. (2010) the resulting inclination distribution was roughly uniform up to 20 degrees, in agreement with the findings of the present paper.

In the mean time, the outer planetesimal disk was slowly grinding into dust by collisional comminution, losing about a factor of 2 in mass in 600 My (Booth et al., 2008). The gravitational interactions between the giant planets and this disk slowly modified the orbits of the former, eventually extracting the planets from their mutual mean motion resonances (Morbidelli et al., 2007; Batygin and Brown, 2010; Levison et al., in preparation). At this point the giant planets became violently unstable. The occurrence of a Late Heavy Bombardment on the terrestrial planets $\sim$ 3.9 Gy ago, strongly suggest that this transition to instability occurred $\sim$ 650 My

after *time zero* (Levison et al., 2001; Gomes et al., 2005; Strom et al., 2005), i.e. well after the formation of the terrestrial planets and the depletion/excitation of the asteroid belt. Due to this instability, the giant planets started to have mutual encounters; Uranus and Neptune were scattered into the outer planetesimal disk and dispersed it. As a result of mutual scattering among the planets and dynamical friction exerted by the outer disk, the planets finally acquired their current orbits (Thommes et al., 1999, 2000; Tsiganis et al., 205; Morbidelli et al., 2007; Batygin and Brown, 2010; Levison et al., in preparation).

The present work strongly argues that, of all possible dynamical paths that the planets could have followed from their original multi-resonant orbits to the current configuration, the real one had to be of the 'jumping-Jupiter' type. In other words the orbital separation between Jupiter and Saturn had to increase abruptly as a result of encounters of both these planets with either Uranus or Neptune. Consequently, the orbits of the terrestrial planets (Brasser et al., 2009) and of the asteroid belt (this work) were only moderately affected by the giant planet instability.

The objects from the outer planetesimal disk and asteroids escaping from the main belt both contributed to the Late Heavy Bombardment of the terrestrial planets, with the former dominating over the latter (this work). However, it is possible that other asteroid belts existed in regions that were stable before the giant planet instability and became unstable since; objects from these belts might have dominated the LHB, but this possibility needs further investigation to be supported. A small fraction of the planetesimals of the outer disk survived on stable trans-Neptunian orbits, corresponding to today's Kuiper belt (Levison et al., 2008).

Thus, the Solar System acquired its current global structure at the LHB time and did not evolve substantially since then.

Acknowledgements:

This work is part of the Helmholtz Alliance's 'Planetary evolution and Life', which RB and AM thank for financial support. Exchanges between Nice and Thessaloniki have been funded by a PICS programme of France's CNRS. HFL is grateful to NASA's Origins of Solar Systems and Outer Planets Program for funding.

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