Vol 435|26 May 2005|doi:10.1038/nature03539 nature

LETTERS

Origin of the orbital architecture of the giant planets of the Solar System

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Planetary formation theories[1,2] suggest that the giant planets formed on circular and coplanar orbits. The eccentricities of Jupiter, Saturn and Uranus, however, reach values of 6 per cent, 9 per cent and 8 per cent, respectively. In addition, the inclinations of the orbital planes of Saturn, Uranus and Neptune take maximum values of ~2 degrees with respect to the mean orbital plane of Jupiter. Existing models for the excitation of the eccentricity of extrasolar giant planets[3–5] have not been successfully applied to the Solar System. Here we show that a planetary system with initial quasi-circular, coplanar orbits would have evolved to the current orbital configuration, provided that Jupiter and Saturn crossed their 1:2 orbital resonance. We show that this resonance crossing could have occurred as the giant planets migrated owing to their interaction with a disk of planetesimals[6,7]. Our model reproduces all the important characteristics of the giant planets' orbits, namely their final semimajor axes, eccentricities and mutual inclinations.

The planetary migration discussed above is a natural result of planet formation. After the giant planets were formed and the circumsolar gaseous nebula was dissipated, the Solar System was composed of the Sun, the planets and a debris disk of small planetesimals. The planets then started to erode the disk, by either accreting or scattering away the planetesimals. The planets migrated because of the exchange of angular momentum with the disk particles during this process[6,7]. Numerical simulations[8] show that Jupiter was forced to move inward, while Saturn, Uranus and Neptune drifted outward. The orbital distribution of trans-neptunian objects is probably the result of such planetary migration[7], and suggests that Neptune probably started migrating well inside 20 AU while the disk was extended up to 30–35 AU (refs 9–11).

During migration, the eccentricities and mutual inclinations of the planets are damped because of their gravitational interaction with the disk particles, in a process known as dynamical friction[12]. However, the planets' orbital periods also change. If initially the planets' orbits were sufficiently close to each other, it is likely that they had to pass through low-order mean motion resonances (MMRs), which occur when the ratio between two orbital periods is equal to a ratio of small integers. These resonance crossings could have excited the orbital eccentricities of the resonance crossing planets. We focus our investigation on the 1:2 MMR between Jupiter and Saturn, as it is the strongest resonance.

In all our simulations, we started with a system where the initial

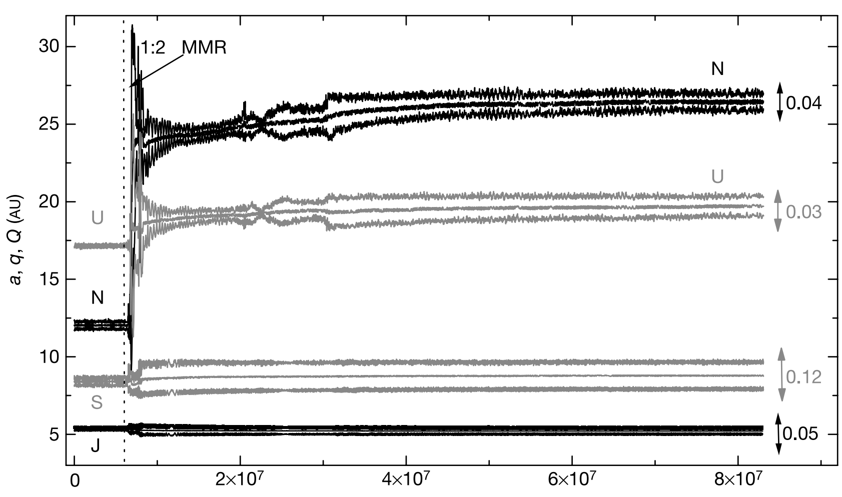

Figure 1 | Orbital evolution of the giant planets. These are taken from a N-body simulation with $35M_{\mathrm{E}}$ 'hot' disk composed of 3,500 particles and truncated at 30 AU. Three curves are plotted for each planet: the semimajor axis (a) and the minimum (q) and maximum (Q) heliocentric distances. U, Uranus; N, Neptune; S, Saturn, J, Jupiter. The separation between the upper and lower curves for each planet is indicative of the eccentricity of the orbit. The maximum eccentricity of each orbit, computed over the last 2 Myr of evolution, is noted on the plot. The vertical dotted line marks the epoch of 1:2 MMR crossing. After this point, curves belonging to different planets begin to cross, which means that the planets encounter each other. During this phase, the eccentricities of Uranus and Neptune can exceed 0.5. In this run, the two ice giants exchange orbits. This occurred in ~50% of our simulations.

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semimajor axis, a, of Jupiter was set to $a_J = 5.45$ AU and Saturn was placed a few tenths of an AU interior to the 1:2 MMR ($a_{1:2} \approx 8.65$ AU). The initial semimajor axes of the ice giants (Uranus and Neptune) were varied in the ranges 11–13 AU and 13.5–17 AU, while keeping their initial orbital separation larger than 2 AU. In all cases, the initial orbits of all the giant planets were nearly circular and coplanar (eccentricities, e, and mutual inclinations, i, $\sim 10^{-3}$). In addition to the giant planets, our simulations included a massive ((30–50)M_E, where M_E is the mass of the Earth) particle disk, consisting of 1,000–5,000 equal-mass bodies, starting just beyond the orbits of the planets, ending between 30 and 35 AU, and with a surface density that falls linearly with heliocentric distance. It has been shown that, although this resolution is not enough to model all aspects of planetary migration[11], it adequately models the macroscopic evolution of the planetary orbits. Both dynamically 'cold' ($e \approx \sin i \approx 10^{-3}$) and dynamically 'hot' ($e \approx \sin i \approx 0.05$) disks were considered. We simulated the dynamical evolution of 43 different systems, using two different N-body codes, SyMBA[13] and MERCURY[14], with a time step of 0.25–0.5 years. In these experiments the self-gravity of the disk was ignored.

A typical example of the evolution undergone by our systems is shown in Fig. 1. At 6.6 Myr, after a period of slow migration on nearly circular orbits, Jupiter and Saturn cross the 1:2 MMR, at which point their eccentricities are quickly excited to values comparable to the ones currently observed. These 'kicks' in eccentricity are the result of the planets jumping over the 1:2 MMR without being trapped, and are qualitatively predicted by adiabatic theory (see Supplementary Information).

The sudden jump in the eccentricities of Jupiter and Saturn described above has a drastic effect on the planetary system as a whole, as shown in Fig. 1. The secular perturbations that Jupiter and Saturn exert on Uranus and Neptune force the eccentricities of the ice giants to increase by an amount that depends on the masses and semimajor axes of all planets[15]. As a result of the 'compactness' of the system, the planetary orbits become chaotic and intersect. When this occurs, a short phase of encounters follows the resonance crossing event. These encounters increase the inclinations of the planetary orbits by 1°–7°. In addition, both ice giants are scattered outward and penetrate the disk. Thus, the flux of small bodies towards Saturn and Jupiter, and hence their rate of migration, increases abruptly. During this fast migration phase, the eccentricities and inclinations of the planets slowly decrease by dynamical friction and the planetary system is stabilized. The planets stop migrating when the disk is almost completely depleted. As shown in Fig. 1, not only their final semimajor axes, but also their final eccentricities, are close to the observed values.

The final orbits of the planets depend on the evolution of the system immediately after the resonance crossing event. Although there were many free parameters in our initial conditions, we found that the final configuration is most sensitive to the initial orbital separation between the ice giants ($\Delta a_{I_1,I_2}$) and, more importantly, to the one between Saturn and the inner ice giant ($\Delta a_{S,I_1}$). In our simulations, $\Delta a_{I_1,I_2}$ ranged from ~2 to ~6 AU, while $\Delta a_{S,I_1}$ ranged from ~2.5 to ~5 AU.

For $\Delta a_{S,I_1} < 3$ AU, the probability that Saturn scatters one of the ice giants to a Jupiter-crossing orbit increases. In such cases, the ice giant is ejected from the system. This happened in 14 (33%) of our runs. All other runs (67%) were successfully completed, that is, all four planets eventually reached stable orbits. Only two cases were found in which no encounters between the giant planets occurred. They both had $\Delta a_{S,I_1} \approx 5$ AU, which means that they were among the least compact systems that we simulated. In these runs, the semimajor axis of Uranus barely reached 16 AU, as in ref. 11. Repeated encounters between the ice giants were seen in all other successful runs. In 13 of them, only the ice giants encountered one another ($\Delta a_{S,I_1} \geq 3.5$ AU). For $\Delta a_{S,I_1} < 3.5$ AU, encounters between Saturn and an ice giant also occurred. Encounters with Saturn affect the dynamics of the Jupiter–Saturn subsystem, allowing the gas giants to maintain their eccentricities against dynamical friction. This type of evolution was observed in 14 of our runs (33%). We note that, in this type of evolution, the duration of the fast migration phase is shorter than in the other cases.

Although we have not thoroughly explored the available parameter space, our experiments enable us to evaluate statistically the proposed excitation mechanism. We distinguish between two classes of runs: first, those in which there were no encounters between an ice giant and a gas giant (class A, 15 runs), and second, those in which Saturn suffered an encounter with one or both ice giants (class B, 14 runs). For each class, we computed the mean and standard deviation of the semimajor axis, proper eccentricity and proper inclination of each planet. Figure 2 shows the comparison between these quantities and the proper orbital elements of the real giant planets. Both classes of runs produce satisfactory results. Planetary orbits with very high eccentricities or inclinations are not produced. However, it is clear from this figure that class B runs (~50% of our successful runs) give a much better match of the outer Solar System. In fact, the three orbital elements of all the real giant planets have values that lie within one standard deviation from the mean values of class B runs.

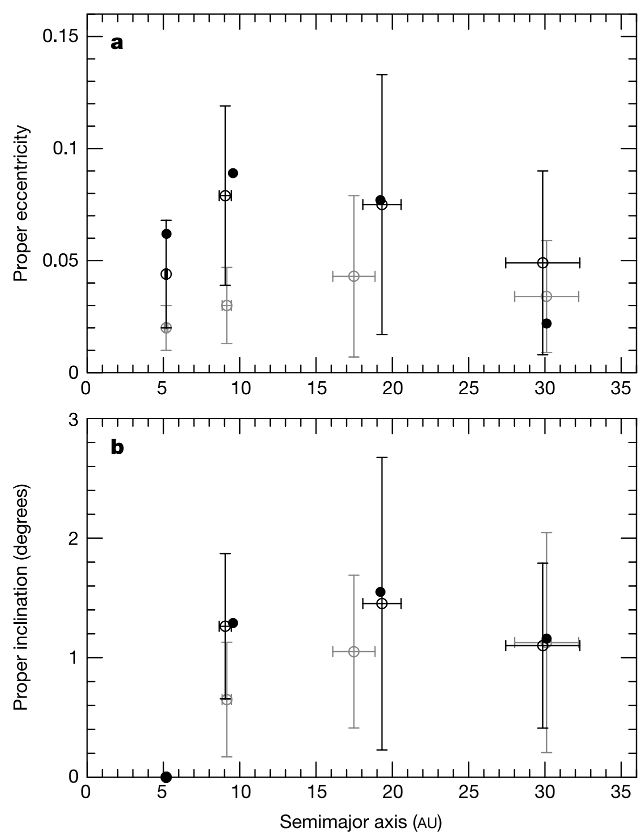

Figure 2 | Comparison of our synthetic final planetary systems with the outer Solar System. **a**, Proper eccentricity versus semimajor axis. **b**, Proper inclination versus semimajor axis. Proper eccentricities and inclinations are defined as the maximum values acquired over a 2-Myr timespan and were computed from numerical integrations. The inclinations are measured relative to Jupiter's orbital plane. These values for the real planets are presented with filled black circles. The open grey circles mark the mean of the proper values for the runs of class A (no encounters for Saturn), while the open black circles mark the same quantities for the runs of class B (see text for the definition of these classes). The error bars represent one standard deviation. The largest values of the proper eccentricity and inclination of our synthetic planets were $e = 0.11$ for Jupiter, $e = 0.17$ and $i = 2.5°$ for Saturn, $e = 0.23$ and $i = 4.5°$ for Uranus, and $e = 0.17$ and $i = 4.0°$ for Neptune.

The final semimajor axes of the planets are an important diagnostic of migration models. The simulations of compact systems in ref. 11 always produced final configurations in which Neptune was at ~30 AU, but Uranus was too close to the Sun. Our model nicely solves this nagging problem. As shown in Fig. 2, class B runs give $a_U = 19.3 \pm 1.3$ AU and $a_N = 29.9 \pm 2.4$ AU, the observed values being $a_U = 19.2$ AU and $a_N = 30.1$ AU. (Here a_U and a_N are the semimajor axes of Uranus and Neptune, respectively.) The final orbital separation of Jupiter and Saturn depends on the amount of mass that they process during the evolution of the system — that is, on the initial mass of the disk. Although larger disk masses favour the stability of the four-planet system, we found that, for disk masses larger than ~(35–40)M_E, the final orbital separation of Jupiter and Saturn tends to be larger than is actually observed. For disks of 50M_E, Saturn was found to cross the 2:5 MMR with Jupiter. In addition, the final eccentricities of the two planets were too small, because they had experienced too much dynamical friction. Indeed, the fact that we reproduce both the semimajor axes and the eccentricities/inclinations in the same integrations is a strong point of our model.

The initial dynamical state of the disk also affects the final state of the planetary system. 'Hot' disks tend to produce systems where the eccentricities for Jupiter and Saturn are larger than in 'cold' disks. The actual disk may indeed have been as excited as we assumed in our 'hot' runs, because of the presence of a large number of Pluto-sized objects[16].

Other compact planetary configurations could lead to the crossing of different MMRs. For reasons of completeness, we studied the crossing of the 2:3 and 1:2 MMRs between (1) Saturn and the inner ice giant, and (2) the two ice giants, by placing Saturn exterior to the 1:2 MMR with Jupiter, and varying the initial positions of Uranus and Neptune. We found that, although some of these resonance crossings may destabilize the orbits of the ice giants, none can excite the orbit of Jupiter.

The survivability of the regular satellites during the planetary encounters is a potential issue with our model. Thus, during eight migration simulations we recorded all encounters deeper than one Hill radius (approximately the distance within which the gravity of the planet dominates over the gravity of the Sun). We then integrated the evolution of the regular satellites of Saturn and the ice giants during a re-enactment of these encounters. We assumed that both ice giants had Uranus's satellite system. We found that in half of the simulations, all of the satellite systems survived the entire suite of encounters (that is, $\sin i, e < 0.05$). Thus, we conclude that the survivability of the satellites is not a problem for the model. However, we note that the irregular satellites would not survive the encounters. Thus, if this model is correct they must have been captured either during or after the 1:2 MMR crossing.

We noticed in our simulations that several particles were trapped on long-lived orbits characteristic of Neptune's Trojan asteroids (two per run, on average, with a lifetime larger than 80 Myr). Their eccentricities reached values <0.1. These particles were eventually removed from the Trojan region, but this is probably an artefact of the graininess of Neptune's migration[8] (although this graininess could also have been responsible for their capture). Jupiter's Trojans are a more subtle issue, described in ref. 17, which also turns out to be a strength of our model.

Thus we conclude that the eccentricities of Jupiter and Saturn are probably the result of the fact that these planets crossed the 1:2 MMR. Other mechanisms[3–5] that have been proposed for the eccentricity excitation of extrasolar planets have neither been applied to our Solar System nor confronted with the large body of constraints that its current structure provides. Our model statistically reproduces all aspects of the orbits of the giant planets. It is consistent with the existence of regular satellites, with the observed distributions of Jupiter's Trojans[17], perhaps with the existence of Neptune's Trojans, and does not contradict the distribution of main-belt asteroids[18].

Received 6 December 2004; accepted 11 March 2005.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements R.G. is grateful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico for financial support of his sabbatical year in the OCA observatory in Nice. The work of K.T. was supported by an EC Marie Curie Individual Fellowship. A.M. and H.F.L. thank the CNRS and the NSF for funding the collaboration between the OCA and the SwRI groups. H.F.L. is grateful to NASA's Origins and PG&G programmes.

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