Origin of the orbital architecture of the Giant Planets of the Solar System

K. Tsiganis[1], **R. Gomes**[2,1], **A. Morbidelli**[1] **and H. F. Levison**[3,1]

[1] *Observatoire de la Côte d' Azur, CNRS, Nice, France*

[2] *ON/MCT and GEA/OV/UFRJ, Rio de Janeiro, Brazil*

[3] *Southwest Research Institute, Boulder, Colorado, USA*

Planetary formation theories [1][2] suggest that the giant planets formed on circular and coplanar orbits. Yet, the eccentricities of Jupiter, Saturn and Uranus reach values of 6%, 9% **and** 8%, **respectively. In addition, the inclinations of the orbital planes of the last three planets take maximum values of** $\sim 2^\circ$, **with respect to the mean orbital plane of Jupiter. Existing models on the excitation of the eccentricity of 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 due to their interaction with a disk of planetesimals [6][7]. Our model reproduces, for the first time, all characteristics of the giant planets' orbits, namely their final semi-major 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 most likely started migrating well inside 20 AU while the disk was extended up to 30–35 AU [9]-[11].

During migration the eccentricities and mutual inclinations of the planets damp 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 1:2MMR between Jupiter and Saturn since it is the strongest resonance.

In all our simulations, we started with a system where the initial semi-major 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 semi-major 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 ($30 - 50\ M_E$) 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' ($e \sim \sin i \sim 10^{-3}$) and dynamically 'hot' ($e \sim \sin i \sim 0.05$) 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 Figure 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 1:2MMR without being trapped, and are qualitatively predicted by adiabatic theory (see Supplementary Information for this *letter*).

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 Figure 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 semi-major axes of all planets (see [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 $1^\circ - 7^\circ$. 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 Figure 1, not only their final semi-major 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 ($\Delta a_{\mathrm{I}_1,\mathrm{I}_2}$) and, more importantly, to the one between Saturn and inner ice giant ($\Delta a_{\mathrm{S},\mathrm{I}_1}$). In our simulations $\Delta a_{\mathrm{I}_1,\mathrm{I}_2}$ ranged from ≈ 2 to ≈ 6 AU, while $\Delta a_{\mathrm{S},\mathrm{I}_1}$ ranged from ≈ 2.5 to ≈ 5 AU.

For $\Delta a_{\mathrm{S,I_1}} < 3$ 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, i.e. all four planets eventually reached stable orbits. Only 2 cases were found in which no encounters between the giant planets occurred. They both had $\Delta a_{\mathrm{S,I_1}} \approx 5$ AU, which means that they were among the least compact systems that we simulated. In these runs, the semi-major 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 ($\Delta a_{\mathrm{S,I_1}} \geq 3.5$ AU). For $\Delta a_{\mathrm{S,I_1}} < 3.5$ 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 parameters space, our experiments enable us to statistically evaluate the proposed excitation mechanism. We distinguish between two classes of runs: (i) those in which there were no encounters between an ice giant and a gas giant (Class A, 15 runs), and (ii) 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 semi-major 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 ($\sim 50\%$ 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.

The final semi-major 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 ~ 30 AU, but Uranus was too close to the Sun. Our model nicely solves this nagging problem. As shown in Figure 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. The final orbital separation of Jupiter and Saturn depends on the amount of mass that they process during the evolution of the system, i.e. on the initial mass of the disk. Although larger disk masses favor the stability of the four-planet system, we found that, for disk masses larger than $\sim 35 - 40\,\mathrm{M_E}$, the final orbital separation of Jupiter and Saturn tends to be larger than is actually observed. For disks of $50\,\mathrm{M_E}$, 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 semi-major 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 (i) Saturn and the inner ice giant, and (ii) 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. We then integrated the evolution of the regular satellites of Saturn and the ice giants during a reenactment of these encounters. We assumed 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 (i.e. $\sin i$, $e < 0.05$). 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 1:2MMR crossing.

We noticed in our simulations that several particles were trapped on long-lived Neptune Trojan orbits (2 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 probably is an artifact of the graininess of Neptune's migration[8]. (Although this graininess could also have been responsible for their capture as well.) Jupiter Trojans are a more subtle issue that is described in[19], but this also turns out to be a strength of our model.

Thus, we conclude that the eccentricities of Jupiter and Saturn are most likely the result of the fact that these planets crossed the 1:2 MMR. Other mechanisms [3]-[5], which have been proposed for the eccentricity excitation of extra-solar planets, have never been applied to our Solar System nor confronted with the large body of constraints that its current structure provides. Our model, for the first time, statistically reproduces all aspects of the giant planet orbits. It is consistent with the existence of regular satellites, with the observed distributions of Jupiter Trojans[17], perhaps with the existence of Neptune Trojans, and does not contradict the distribution of main-belt asteroids[18].

References

1. Pollack J.B., Hubickyi O., Bodenheimer P., Lissauer J.J., Podolack M., and Greenzweig Y. Formation of the Giant Planets by Concurrent Accretion of Solids and Gas Icarus 164, 62-85 (1996).

2. Lubow S.H., Seibert M., and Artymowicz P. Disk Accretion onto High-Mass Planets. Astroph. J. 526, 1001-1012 (1999).

3. Goldreich P., and Sari R. Eccentricity Evolution for Planets in Gaseous Disks. Astroph. J., 585, 1024-1037 (2003).

4. Papaloizou J.C.B., Nelson R.P., and Masset F. Orbital eccentricity growth through disk-companion tidal interaction. Astron. Astrophys. 366, 263-275 (2001).

5. Zakamska N. L. and Tremaine S. Excitation and Propagation of Eccentricity Disturbances in Planetary Systems. Astron. J. 128, 869-877 (2004).

6. Fernandez J.A., and Ip W.-H. Some dynamical aspects of the accretion of Uranus and Neptune - The exchange of orbital angular momentum with planetesimals. Icarus 58, 109-120 (1984).

7. Malhotra R. The origin of Pluto s orbit: implications for the Solar System beyond Neptune. Astron. J. 110, 420-432 (1995).

8. Hahn J.M., and Malhotra R. Orbital evolution of planets embedded in a planetesimal disk. Astron. J. 117, 3041-3053 (1999).

9. Gomes R. The origin of the Kuiper Belt high-inclination population. Icarus 161, 404-418 (2003).

10. Levison H.F., and Morbidelli A. The formation of the Kuiper belt by the outward transport of bodies during Neptune's migration. Nature 426, 419-421 (2003).

11. Gomes R.S., Morbidelli A., and Levison H.F. Planetary migration in a planetesimal disk: Why did Neptune stop at 30 AU? Icarus 170, 492-507 (2004).

12. Kokubo E., and Ida S. Orbital evolution of protoplanets embedded in a swarm of planetesimals. Icarus 114, 247-257 (1995).

13. Duncan M.J., Levison H.F., and Lee M.H. A Multiple Time Step Symplectic Algorithm for Integrating Close Encounters. Astron. J. 116, 2067-2077 (1998).

14. Chambers J.E. A hybrid symplectic integrator that permits close encounters between massive bodies. MNRAS 304, 793-799 (1999).

15. Murray C., and Dermott S.F. Solar System Dynamics. Cambridge University Press, Cambridge, U.K. (1999).

16. Stern S. A. On the number of planets in the outer solar system - Evidence of a substantial population of 1000-km bodies. Icarus 90, 271-281 (1991)

17. Morbidelli A., Levison H.F., Tsiganis K., and Gomes R. Nature, XXX (2005)

18. Gomes R., Tsiganis K., Morbidelli A., and Levison H.F. Nature, XXX (2005)

Correspondence. Alessandro Morbidelli, Observatoire de la Côte d'Azur, B.P. 4229, 06304 Nice Cedex 4, France. Tel: 33-492003126; email: morby@obs-nice.fr

Acknowledgments. R.G. is grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico for the financial support for his sabbatical year in the OCA observatory in Nice. The work of K.T. was supported by an

EC Marie Curie Individual Fellowship (contract No HPMF-CT-2002-01972). A.M. and H.L. thank the CNRS and the NSF for funding the collaboration between the OCA and the SwRI groups. H.L. is grateful to NASA's Origins and PG&G programs.

Figure Captions:

Figure 1: Orbital evolution of the giant planets. These are taken from a $N-$body simulation with $35\,\mathrm{M_E}$ 'hot' disk composed of $3,500$ particles and truncated at 30 AU. Three curves are plotted for each planet: the semi-major axis and the minimum (q) and maximum (Q) heliocentric distances. The separation between the upper and lower curves is a measure 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 $\sim$50% of our simulations.

Figure 2: Comparison of our synthetic final planetary systems with the outer Solar System. A) Proper eccentricity vs. semi-major axis. B) Proper inclination vs. semi-major 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 dots. The open gray dots mark the mean of the proper values for the runs of Class A (no encounters for Saturn), while the open black dots 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 of the measurements. The largest values of the proper eccentricity and inclination of our synthetic planets were $e = 0.11$ for Jupiter, $e = 0.17$ and $i = 2^\circ.5$ for Saturn, $e = 0.23$ and $i = 4^\circ.5$ for Uranus and $e = 0.17$ and $i = 4^\circ.0$ for Neptune.

Figure 1:

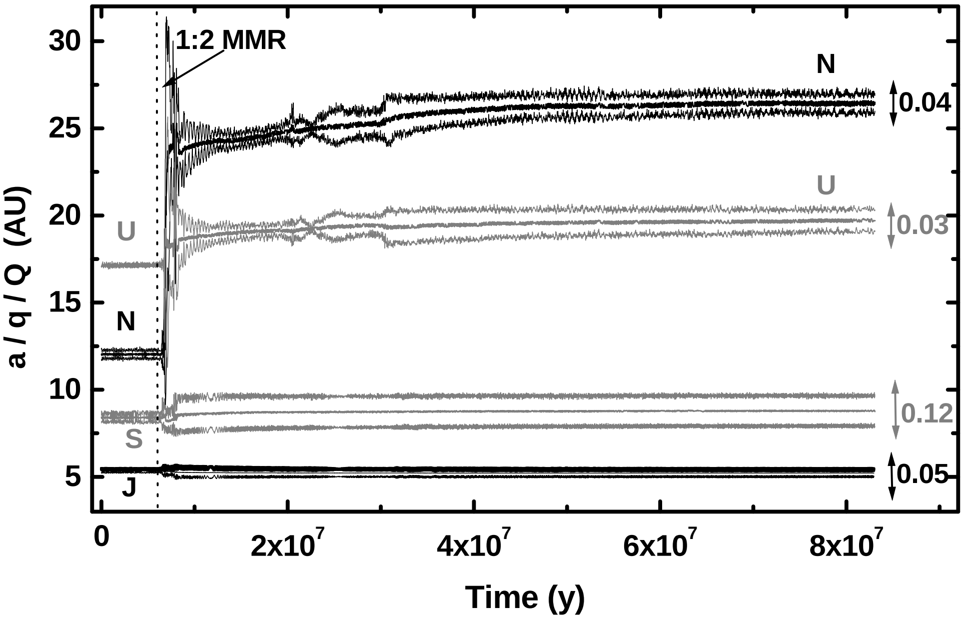
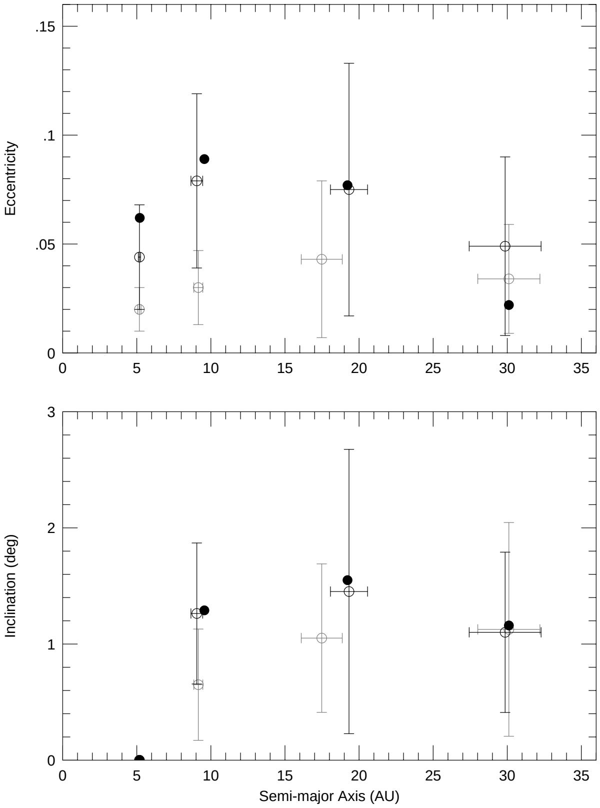

1:2 MMR
N
0.04
U
0.03
U
N
S
0.12
J
0.05
a / q / Q (AU)
30
25
20
15
10
5
0
2x10^7
4x10^7
6x10^7
8x10^7
Time (y)

Figure 2:



Eccentricity
.15
.1
.05
0
0
5
10
15
20
25
30
35
Inclination (deg)
3
2
1
0
0
5
10
15
20
25
30
35
Semi-major Axis (AU)