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GLOBAL CONSEQUENCES OF THE ACCRETION OF THE OUTER SOLAR SYSTEM

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RESUMEN

Presentamos una discusión del proceso que dió origen al sistema solar exterior con especial énfasis en su estructura orbital. La influencia global que este proceso ha tenido sobre todo el sistema solar es también discutida a la luz de la evidencia observacional. Se presentan argumentos que muestran que, desde la nube de Oort y hasta la región de los planetas terrestres, todo el sistema solar se vió profundamente afectado por este proceso.

ABSTRACT

The present status of our knowledge about the accretion process of Uranus and Neptune is discussed, emphasising in the possible origin of the orbital structure at the time of formation of the outer solar system. The most important influences of this process over the entire solar system are also discussed: in the inner planetary region, contributing to the formation of the planetary atmospheres and water reservoirs; in the asteroid and Kuiper belts, sculpting their primordial structures, and in the outer edge of the solar system, building up the Oort cloud of comets.

Key Words: **COSMOGONY — NUMERICAL SIMULATIONS — OUTER PLANETS — SOLAR SYSTEM**

1. INTRODUCTION

There has been considerable progress in our knowledge about how planetary systems, and our own solar system, formed based on both theoretical modelling and observations.

Numerical simulations of the late accretion of Uranus and Neptune (Fernández & Ip 1984, 1996; hereafter FI84 and FI96, respectively), which rest on the planetesimal paradigm (Safronov 1972), have shed light on the origin of important features observed in the outer solar system.

Recent improved numerical simulations (Brunini & Fernández 1998a, 1998b; hereafter BF98a, BF98b) carried out, for the first time, by N-body numerical integrations of the equations of motion, have shown that the final orbits of the obtained synthetic outer planets lie generally very near mean motion commensurabilities. Resonant coupling has played a major role in the dynamical evolution of the outer planetary system. Moreover, variations in the orbital spacing of the outer planets may have substantially affected the dynamical structure of the entire solar system, changing the locations and widths of the niches of orbital stability it posses.

During the accretion process, the orbit of Neptune, and to a lesser extent those of Uranus and Saturn experienced a large drift, due to the exchange of angular momentum with the interacting planetesimals (Safronov 1972; FI84). This planetary migration may have played an important role during the late accretion phase of the outer solar system, being recently claimed as the responsible for the presence of Pluto in its eccentric and inclined orbit in 3:2 resonance with Neptune (Malhotra 1995), and of the global quasi-resonant structure of the outer solar system (FI96).

Less than 50% of the solid material originally present in the system as planetesimals contributes to the formed protoplanets, the rest being mostly ejected by the massives Jupiter and Saturn, reaching very large

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heliocentric distances, where they are eventually subject to external perturbers such as passing stars, giant molecular clouds, and the Galactic tidal force. Under certain conditions, a fraction of these bodies end up stored in a comet reservoir called the Oort cloud. The structure of the Oort cloud should depend on the natal Galactic environment of the solar system.

A certain fraction of the original mass in the Uranus-Neptune region may eventually reach the innermost regions of the solar system. A phase of strong scattering of bodies from the Uranus-Neptune region to the inner solar system lasted for a period of $\sim 4 \times 10^7$ yr. Around 10 to 20 Earth masses may have reached the region of the terrestrial planets. This large influx of material over such a small volume in space has strongly influenced, in several ways, the entire population of primordial bodies in this region.

The tilt of Uranus spin axis, the Pluto-Charon binary system and Triton may be fossil records of an early substantial population of large planetoids in the early outer planetary region (Stern 1991; Parisi & Brunini 1996). As a consequence of the dynamical interaction with the already formed proto-Neptune, some of them may reach large heliocentric distances (BF98), invading the transneptunian region, and therefore, exciting large orbital eccentricities and inclinations in that region (Morbidelli & Valsecchi 1997; Brunini & Melita 1998). This process may have contributed in a substantial way to the sculpting of the primordial Kuiper belt.

In this paper, we will present several arguments, based in the most modern theoretical and observational results, supporting that the macro-accretional process of the outer solar system have strongly influenced different regions and populations in the early solar system.

The paper is organized as follows: in section 2 we outline the main details of the numerical algorithm and of the model used to carried out the most recent numerical simulations of the formation of the outer solar system. Section 3 is devoted to present the most relevant results of these numerical simulations. Section 4 is divided in several subsection, each one devoted to discuss the way in which the accretion of Uranus and Neptune influenced a given primordial population in the solar system. The last section is left for the conclusions.

2. NUMERICAL SIMULATIONS OF THE ACCRETION OF THE OUTER SOLAR SYSTEM

The most modern numerical simulations of the formation of the outer solar system (BF98) were based on the numerical integration of the equation of motion of an ensemble of massive bodies by means of a second order simplectic integrator (Wisdom & Holman 1991). This integrator, developed at La Plata Observatory, is able to account for close planetary encounters, in a similar way as the one developed by Levison & Duncan (1994).

A good compromise between a realistic way to consider the growth of Uranus and Neptune by accumulation of smaller embryos, and a practicable one with the present computational resources, is to assume that Jupiter and Saturn had already reached their present mass, but that a large number of embryos were still growing at greater distances from the Sun. It is currently accepted that when Jupiter and Saturn were fully grown, embryos of masses ranging from a fraction to several $M_\oplus$ could have been located in the outer solar system (Lissauer 1993).

Therefore, in all the simulations, Jupiter and Saturn were already present with their current masses and orbits, whereas a swarm of N bodies of equal mass was distributed in a flat structure between 15 and 35–45 AU. The adopted radial distribution was $dN/da \propto a^{-\gamma}$ with $\gamma = 1/2$, which follows some models of the mass distribution in the protoplanetary disk (Weidenschilling 1977). Small initial eccentricities and inclinations randomly distributed with maximum values ranging from 0.001 up to 0.01 were adopted. The total initial mass of the entire swarm of bodies was defined as a factor $f > 1$ of the combined mass of the current Uranus and Neptune. As the initial mass in the planetesimal swarm is typically of 1.5 to 2.5 times the combined mass of Uranus and Neptune, the planetesimals have initial masses in the range $10^{-2} - 10^{-3} M_U$, being M_U the present mass of Uranus. Planetary perturbations were fully included in all the reported numerical simulations.

Up to the present, we have performed 65 runs with slightly different initial number N of planetesimals (500 and 1000).

3. RESULTS

In 31 out of 65 of the computed runs the accretion process by mutual collisions of the planetesimals evolved to the formation of two planets, though in some cases one or three large planets were obtained. When only

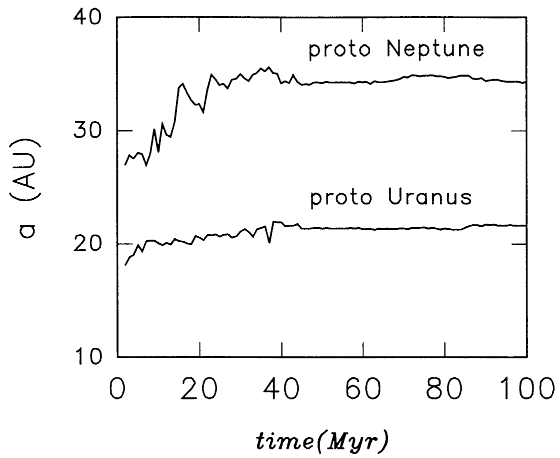

Fig. 1. Time evolution of the semimajor axis of the outer planets for one of the runs.

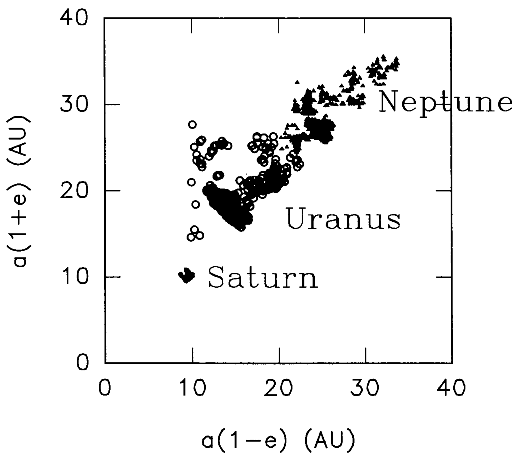

Fig. 2. Perihelion vs. aphelion distances reached by proto Uranus and proto Neptune in one of the runs.

one massive planet is formed, its orbit lies beyond 30 AU. Full data of these synthetic planetary systems can be found in BF98a and BF98b. This diversity might be interpreted as a possible indication of the diversity of generic planetary systems. Figure 1 shows the orbital evolution of the proto-Uranus and proto-Neptune for a representative run.

The orbital migration, already reported in previous simulations (FI84; FI96; BF98), is explained as due to the exchange of angular momentum with the interacting planetesimals. The growing Proto-Uranus and proto-Neptune do not possess masses large enough to eject a substantial number of planetesimals from the solar system. Therefore, after repeated close encounters with these protoplanets, the unaccreted planetesimals end up falling under the gravitational control of Saturn and Jupiter, which finally eject them from the planetary region. As a consequence of this dynamical picture, proto-Uranus and proto-Neptune (and to a lesser extent Saturn) lose orbital angular momentum expanding their orbits, whereas Jupiter migrates inwards.

The average of the final orbital eccentricities and inclinations of the outer planets in the runs are $< e_u >= 0.08, < i_u >= 1^\circ$ and $< e_N >= 0.1, < i_N >= 4^\circ$, but as a consequence of close encounter with other proto-planets, the orbital eccentricities may reach very high values during the accretion process (e.g. 0.2 or more).

As it is shown in Figure 2, each protoplanet sweept large zones in heliocentric distance, in such a way that almost all places between Saturn orbit and far beyond the orbit of Neptune are occupied at some time for one

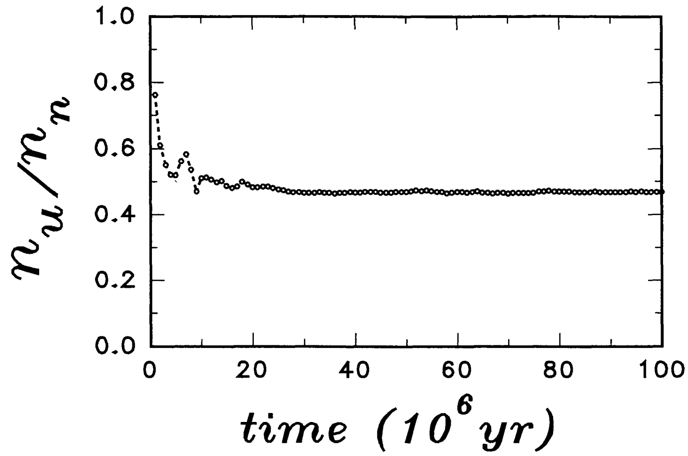

Fig. 3. Evolution of the ratio between the mean motions of the proto planets.

of the two protoplanets. We believe that this situation is responsible for the formation of no more than two planets in the outer solar system. However, after the end of the process of intense encounter rate (lasting for $\sim 10^7$ yr), the orbits of the protoplanets do not cross anymore because of the existence of the conservation of the total angular momentum in the planetary motion. In order to keep constant the total angular momentum of the system, when the eccentricity of proto-Uranus increases, the one of proto-Neptune decreases and vice-versa. This mechanism acts as a protection against dangerous close encounters.

In the present solar system the Jovian planets are very close to mean motion commensurabilities: 2:5 between Jupiter and Saturn; 1:3 between Saturn and Uranus; and 1:2 between Uranus and Neptune. It has been recently argued (FI96) that the combined effect of resonance and a secular variation in the orbital semimajor axis such as the planetary migration experienced by the outer planets, may be a successful mechanism to produce these stable orbital configurations. The process of capture in mean motion resonance may be summarized as follows: during the secular excursion of the semimajor axes of the planets, they may cross heliocentric distances such that the orbital periods fall in some resonance. In some circumstances, a resonance can provide enough energy as to counteract the variations in semimajor axis of the planets, trapping them in a stable near-resonant configuration. The temporal evolution of the ratio between the mean motions of the protoplanets is shown in Figure 3 for some of the runs, given support to the resonant capture mechanism. More rigorous tests of the resonant capture hypothesis, involving surveys of the behaviour of appropriate dynamical variables, can be found in BF98b.

The masses of proto-Uranus and proto-Neptune grow very fast. In all the simulations we have observed that the time scale of accretion of Uranus and Neptune would demand between several 10^7yr and 10^8yr, a time scale which is consistent with the possible presence of a nonnegligible amount of hydrogen and helium in Uranus and Neptune envelopes, of the order of 1.6 $M_\oplus$ and 1.1 $M_\oplus$ respectively (Pollack et al. 1996). It suggests that the time scale of planet formation in the outer solar system could have not been much longer than the time scale of dissipation of the gaseous component of the nebula.

The large radial excursions experienced by the protoplanets, such as the ones shown in Figure 1, bring them into zones not depleted of planetesimals, thus substantially extending their feeding zones, and avoiding the isolation. This is one of the reasons of such a fast accretion rate. Another major difference with previous simulations is that our code is able to treat accurately encounters between bodies on non-crossing orbits, a fact that previous codes, base on statistical approaches, were not able to properly account.

4. GLOBAL CONSEQUENCES OF THE ACCRETION OF THE OUTER PLANETS

4.1. *On the Inner Planetary Region*

A large fraction of the bodies scattered by the accreting proto-Uranus and proto-Neptune fall under the gravitational control of Saturn and Jupiter. Once this happens the dynamical evolution of the scattered bodies is characterised by a fast random-walk in perihelion distance q in such a way that a fraction of them become Mars, Earth and even Venus crossers before being ejected in hyperbolic or near parabolic orbits.

The cumulative mass reaching the region of the terrestrial planets is found to be of the order of 10 to 20 Earth masses, becoming potential impactors of these four planets. The phase of early strong bombardment of the terrestrial planets due to scattered planetesimals from the Uranus-Neptune region reached its maximum near $\sim 10^7$ yr, lasting, but at a slower rate, for $\sim 4 \times 10^7$ yr. About 20 times the amount of water contained in the oceans could have reached the Earth from this bombardment of icy material (Fernández & Ip 1997), but this is a very uncertain result at this point. The answer depends on whether or not the Earth and the other terrestrial planets were already formed when the influx of planetesimals from the outer planetary region reached its peak. If they were still in the process of accretion most of the accreted volatile material might have been lost in subsequent mega-impacts.

Some of the planetesimals (whose masses we found to be $\sim 10^{24}$ gr, on average) may eventually collide onto the Sun, enrichening its convective regions with heavy elements. Yet, wheter or not this process affects the present observed solar neutrino flux is a rather controversial point (Jeffery et al. 1998; Dalsgaard & Gough 1998).

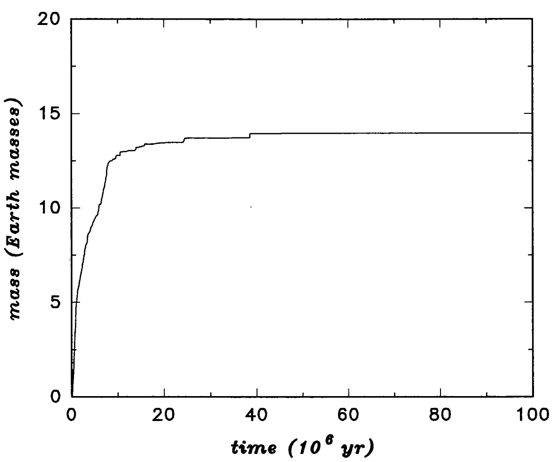

Fig. 4. Evolution of the mass reaching the region of the terrestrial planets (average over 65 runs).

4.2. *On the Collisional Evolution of the Primitive Asteroid Belt*

Studies of the collisional evolution of the asteroid belt have suggested that the present size distribution could be the remnant of an initial population modified by an intense collisional process, which also altered the shapes and rotation rates of these objects.

In order to study asteroid collisional evolution, Davis et al. (1994) tested the results produced by scaling laws, different starting populations and choices of the critical collisional parameters, to find which are consistent with observations of the real asteroid population. These authors reach the conclusion that simple energy scaling does the best in reproducing the observed asteroid belt, but the starting population they were forced to use was formed by two power law distributions with a transition radius of 50 km. This peculiar initial population was adopted from the requirements that the initial total mass of the belt is not much larger than the current one, and larger and larger asteroids have been less and less depleted by impact disruption. This ad-hoc assumption was made in order to preserve the basaltic crust of Vesta over the solar system history (Davis et al. 1985), receiving just the right amount of cratering collisions to form its family (Binzel & Xu 1993), but not impacts so large and frequent as to fracture the crust and thoroughly mix it with the underlying olivine-rich mantle material.

According to the planetesimal accretion theory (Davis et al. 1979), an initial asteroid belt with an amount of mass similar to the present one is not enough to form a body as large as Ceres in a time shorter than the age of the solar system. So, it looks necessary to find a process which joins all these constraints in an unified evolutionary scheme, allowing a massive initial belt but reducing very fast the number of asteroids to maintain a low impact rate, and preserving Vesta's thin crust.

Brunini & Gil Hutton (1998) and Gil Hutton & Brunini (1998) have numerically simulated the collisional evolution of the primitive asteroid belt due to a bombardment from scattered objects coming from the Uranus - Neptune zone.

The collisional process due to scattered comets allows the use of single exponent incremental size distributions for the initial belt which, after 4.5×10^9 years of collisional evolution, reaches final distributions matching very well the observed population.

Since this bombardment was extremely efficient removing mass in a very short time, Gil Hutton & Brunini (1998) always obtained belts with less than $0.001 M_\oplus$ after $\approx 2 \times 10^7$ years. This result allows processes with an important initial mass without losing the chances that Vesta preserved its basaltic crust and shows that the choice of two power law distributions made by Davis et al. (1994) for their starting population agrees with our code output after the early bombardment from planetesimals of the outer solar system. In addition, since the effects of the cometary infall are more important in the inner belt (due to the decrement of relative velocities and increment of volume with increasing heliocentric distances) this region was depleted very fast and efficiently, increasing the possibilities that Vesta survives almost intact.

4.3. *On the Primordial Sculpting of the Kuiper Belt*

A few dozens of trans-Neptunian objects have been discovered at the time and their main dynamical characteristics can be summarized as follows. Most of the Kuiper belt objects (KBO's) with well determined orbits are associated with an exterior Neptune resonance. The most populated is the 3:2 resonance, and a few can be found in the 4:3 and 5:3 resonances. Curiously enough, no object (with the exception of a possible candidate) has been discovered in the 2:1 resonance, although if there were a population at that location, it would have been observable by the most recent surveys (Jewitt et al. 1998).

Following the outward migration of Neptune, the mean motion resonances also migrated with it, sweeping at each moment the resonant KBOs. According to a well known theory in celestial mechanics, most of the sweept bodies are captured in mean motion resonance, and thus, after Neptune reached its present position (Malhotra 1995), an accumulation of KBOs in mean motion resonances is expected. Malhotra (1993, 1995) explored this model assuming an exponential migration for the outer planets that, in general lines, matches our results. It is remarkable that her numerical simulations correctly reproduced the orbital inclination and eccentricity distribution of the observed KBOs in the 2/3 resonance with Neptune. However, in this simplified model, a large number of objects should be also present in the 1/2 resonance, while none has been discovered up to now. More recent numerical simulations (Brunini & Melita 1998) have given a new support to Malhotra's scenario: when noise is added to the orbital expansion of Neptune (as in Fig. 1) the efficience of the 1/2 resonance in capturing KBOs is substantially reduced.

The physical radii of the discovered objects are ~ 170 km. Accretion studies have determined that, for those objects to grow up to those sizes, the inner belt should have been $30 - 50$ times more massive than it is observed at present (Stern & Colwell 1997). Thus, a depletion mechanism capable of reducing the belt's mass down to its present value must have taken place. The most plausible response is associated with the invasion of the Kuiper belt by large planetoids, scattered fron the Uranus-Neptune region.

Figure 5 shows the radial distribution of the protoplanets in one of the runs that resulted in the formation of two massive planets, for different times. In short time scales, of the order of few 10^7 yr, up to 11 protoplanets are present in the region beyond Saturn. It is worth noting that some large embryos reach semimajor axes in the region of the Kuiper belt ($\sim 30 - 60$ AU) remaining there for several 10^6 yr. The invasion of those planetoids would provoke both the direct removal of the belt bodies by encounters, and the excitation of their

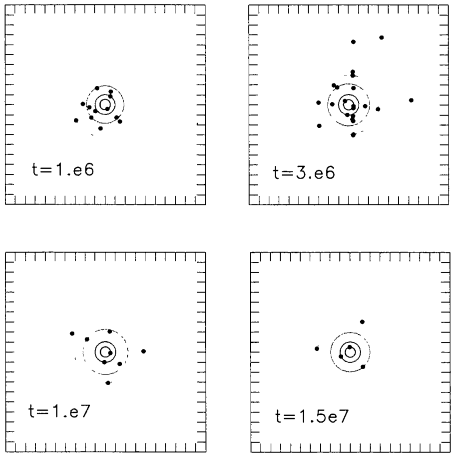

Fig. 5. Evolution of the number and radial distribution of protoplanets for one of the runs.

eccentricities, which would bring them to a regime where mutual collisions are disruptive (Melita & Brunini 1998). In this regime, KBOs with diameters smaller than 50 km should be collisional fragments, rather than primordial bodies (Davis & Farinella 1997).

4.4. *The Build up of the Oort Cloud*

The scattering of bodies by the accreting Jovian planets send them to large heliocentric distances where the action of external perturbers are able to raise the perihelia of a certain fraction of the scattered bodies above the planetary region, where they would remain trapped in the so called Oort reservoir, until other external perturbations would re-inject their perihelia into the planetary region (the "new comets") or eject them to interstellar space. This is the basis of the theory developed by Oort (1950).

Does the scattering of bodies by the accreting Jovian planets occurred while the Sun was still in its dense natal environment? The answer is probably affirmative for Jupiter and Saturn, while results of our numerical simulations show that it is more uncertain for Uranus and Neptune.

Recent numerical simulations of the formation process of the Oort cloud (Fernández & Brunini 1998) shows that if this were the case, the formation and survival of an inner core of comets in tightly bound orbits as a result of strong perturbations from a dense Galactic environment would be possible. The semimajor axes of comets in the core might range between several hundreds and a few thousands AU. Its population and range of semimajor axes will depend on the particular characteristics of the Galactic environment of the early Sun (density of molecular gas, number density of neighbour stars, etc.) and on how long it could survive before dissipation. A very dense environment would favor a more centrally condensed core of comets. Such a core might have been left as a replenishment source of the classical Oort cloud through a slow diffusion process by penetrating encounters with giant molecular clouds and very close stellar passages.

Future improvements in space telescopes and detectors will allow us to explore the circumsolar region at several hundreds AU to the Sun where the existence of such a core may be tested observationally, providing a new insight into the early Galactic environment of the Sun.

5. CONCLUSIONS

Much progress has been done in our understanding of the formation of the outer planets and scattering of the residual mass from the early theoretical research of Safronov (1972). Recent N-body simulations of this process revealed that this was one of the most collective phenomena during the early stages of our planetary system.

From the region of the terrestrial planets up to its outermost boundary, the Oort cloud of comets, the solar system has suffered the influence of the accretion of Uranus and Neptune. In some cases, the subsequent evolution of entire populations of minor bodies in the solar system was predetermined by this process. This is the case of the main belt of asteroids, where the distribution of diameters was sculpted by the early bombardment of scattered planetesimals from the Uranus-Neptune region. The formation of the Oort cloud of comets is a direct by-product of the scattering of these residual planetesimals.

The Earth may have acquired a substantial (if not all) fraction of its oceans through mega-impacts with scattered bodies from the outer solar system. Therefore, the accretion of Uranus and Neptune could have played a decisive role in the rise and subsequent evolution of life on the Earth.

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