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POTENTIAL SOURCES OF TERRESTRIAL WATER CLOSE TO JUPITER REGION

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ABSTRACT

We search for possible carriers of terrestrial ocean water. On the basis that it was not endogenic, we explore possible sources of ice-rich planetesimals which may have collided with the Earth after the heavy planetesimal bombardment, once the young Earth was capable to keep the accreted water. Comets were thought to be the main carriers of water, but the Deuterium/Hydrogen isotopic ratio observed in comets Halley, Hale-Bopp and Hyakutake was found to be higher than in Earth's ocean water. This discrepancy seems to discard comets as the main water carriers. We have then to find alternate sources of carriers in the protoplanetary disk. We analyzed numerically two possible sources: one of bodies close to Jupiter's orbit, and the other one in the outer part of the main asteroid belt. Some preliminary results of our integrations will be discussed in this presentation.

I. INTRODUCTION

The origin of water on Earth is one of the most important issues in cosmogony with relevance to the understanding of the origin of life on Earth. It is well known that the meteorites show a gross correlation between their water content and their original heliocentric distance. The planetesimals formed in the Earth's zone should have had a negligible water content, due to the high temperatures at which the grains accreted. In addition, any water accreted from these planetesimals should have been lost in the Earth's accretion process. Therefore, the prevailing opinion was that the water present on Earth came from the outer solar system, carried by comets colliding with the young Earth (Oro 1961). However, the deuterium enrichment observed in the water molecules of comets Halley, Hyakutake and Hale-Bopp is about twice as large as that of seawater (Bockelée-Morvan et al. 1998). From this observation, it was argued that most of the water was supplied by bodies formed in the protoplanetary disc closer to the sun where the water could have sublimated and re-condensed (Morbidelli et al. 2000). This might have happened around the snowline boundary where the water might have remained in the vapour phase for long periods of time before recondensing. The molecules of deuterated water by exchange of deuterium with the molecular hydrogen, might have reduced their D/H ratio according to the reaction (Delsemme 1999)

$$HDO + H_2 \rightarrow H_2O + HD$$

Our aim is to explore potential sources of seawater close to the snowline. The suitable candidates are asteroids of the outer main belt and Jupiter's Trojans. We give a preliminary account of our numerical simulations below.

II. THE NUMERICAL METHOD

We integrated the orbits of test particles created in the appropiate region. We used the integrator EVORB developed by Adrián Brunini of La Plata Observatory and which has been used in several dynamic problems (Fernández et al. 2002). This integrator uses the Bulirsch-Stoer subroutine to calculate close encounters, for which a influence sphere of three Hill's radius was adopted. This integrator was tested for the conservation of energy, finding that the energy keeps constant for ten millions years with oscilations of 10^{-9} in their relative value. The constant of Jacobi was also tested integrating only one planet with one particle noting that it keeps for hundreds of encounters in extreme conditions with an oscillation of only 10^{-4} (T. Gallardo, private communication). Besides we checked the evolution of the orbit elements of the Earth, finding similar oscilations to other integrations in the literature. (Brower and van Woerkom 1950)

A programme was recently incorporated that allows to apply random increments of speed to the particles. It was tested in Trojans, and some of them which were stable for more than one hundred million years escaped and had encounters with the Earth. This was done on the basis of some recent work showing that Trojan orbits are destabilized by colisional ejection. (Marzari et al. 1997)

III. SAMPLES OF PARTICLES ANALYSED

III.1 Trojans

A sample of 200 particles was generated around the orbit of Jupiter, with orbital elements semimajor axis (a), eccentricity (e) and inclination (i) taken at random within the following ranges:

$a_J - 0.2\ AU < a < a_J + 0.2\ AU$

$e_J - 0.01 < e < e_J + 0.01$

$1.0^o < i < 2.0^o$

in which a_J and e_J are the semimajor axis and the eccentricity of Jupiter.

The angles longitude of ascending node (Ω), argument of perihelion (ω) and mean anomaly (M) were chosen randomly between 0 and 2π. The resulting perihelion and aphelion distances were comprised within the following ranges:

$4.72\ AU < q < 5.17\ AU$

$5.20\ AU < Q < 5.70\ AU$

III.2 Asteroids of the main belt

A sample of 250 particles was generated, with orbital elements taken at random within the following ranges:

3 AU < a < 4.5 AU.

0 < e < 0.1

0 < i < 0.1 rad

The angles Ω, ω and M were distributed randomly between 0 and 2π. The resulting perihelion and aphelion distances were comprised within the following ranges:

2.7 AU < q < 4.5 AU

3.3 AU < Q < 4.95 AU

These values result from the consideration of the minimum radius of the disc of protoplanetary accretion in which water could condense, inside the orbit of Jupiter.

IV. ANALYSIS OF RESULTS

IV.1 Preliminary conclusions of Trojans

From 200 particles in Jupiter's zone, 73 were stabilized as Trojans after 2 millions years (Myr). Then this sample was duplicated by clonation, through random increments with a maximum of $5x10^{-3}$ AU to each component of their positions, and $5x10^{-3}$ AU/year to each component of their velocities.

After 120 Myr, 107 particles were left out of the duplicated sample of 146. From the 39 that were lost, one collided with Jupiter and another one had a close encounter with the Earth.

A pending work is to analyse the evolution of all the escaped particles to derive the fraction of them that enter into the inner planetary region. It is noted that some of the escaped particles have a periodic oscillation of the mean eccentricity for a very long period (some Myr) before the libration of the critical angle break and start to circulate as we can see in figure 1. The possibility that a secular resonance is operating will be analyzed in a future publication.

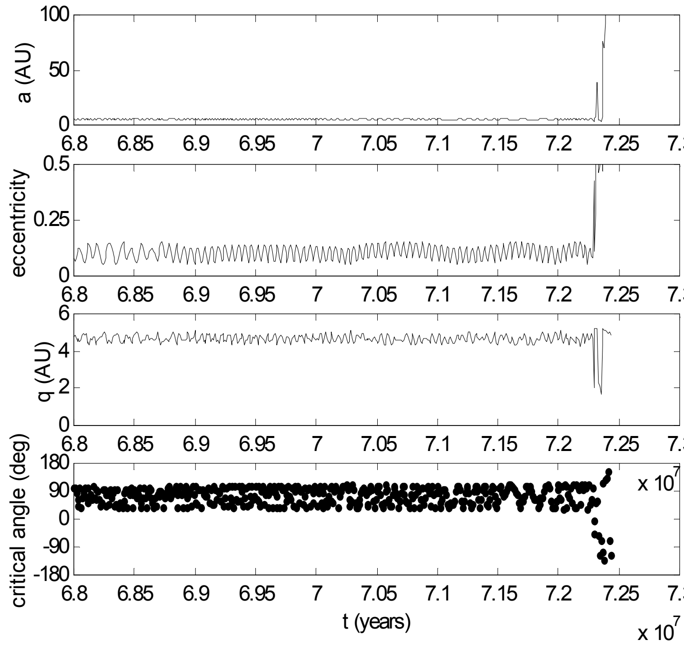

Fig. 1 – Evolution of particle No. 12, which had one encounter with the Earth.
Note the periodic oscillation of the mean eccentricity, with a period ~ one Myr.

Recently, random increments of velocity were applied on 100 particles which survived as Trojans for 100 Myr. Thus was added to each component of the velocity a random number between - 7.9 x 10^{-3} AU/year ($0.65/\sqrt{3}$ Km/s) and + $0.65/\sqrt{3}$ Km/s.

From these 100 particles which received velocity increments, 25 have already escaped. Among them, two had encounters with the Earth, one of them 97 encounters in a period of 3.84×10^5 years and the other one three encounters in about 2.4×10^4 years. (See figure 2 and figure 3)

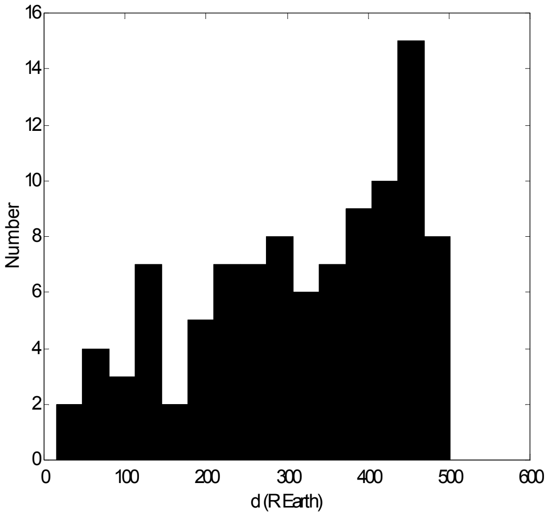

Fig 2 Histogram of encounters with the Earth

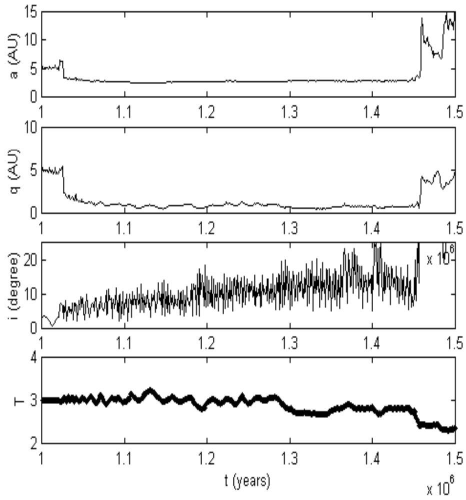

Fig 3 Evolution of orbital elements of Trojan No.13 during its encounters with the Earth

Therefore for three particles which had a perihelion distance q<1 AU for some time, the probability of collision with the Earth is not null. The collision probability of a given particle k per orbital revolution was preliminary determined using the formula: (Öpik, 1951)

$$p_k = \frac{{\sigma_k}^2 U_k}{\pi \sin i_k \left| U_{xk} \right|} ,$$

where σ_k is the gravitational radius of collision, U_k is the encounter velocity in units of the planet's orbital velocity, and U_{xk} is the component of U_k along the radius vector Sun-planet. The weighted collision probability per particle was then computed from

$$P = \frac{1}{N} \sum_{k=1}^{N} p_k \Delta t_k \Big/ a_k^{3/2}$$

in which $p_l = 0$ when the escaped particle l does not cross the orbit of the Earth. Δt_k is the time interval that a given particle remained with q<1 AU (if this never happened $\Delta t_k=0$), a_k is the semimajor axis of the orbit of each particle.

The calculated value is:

$P= 2.4 \times 10^{-4}$

For computing the initial mass of Trojans we used for the nebula surface density at distance $r(AU)$:

$\sigma = \frac{F\sigma_o}{r^{1.5}}$ where σ_o is the surface density of solid matter at r = 1 AU, σ is the corresponding density at r and F is a factor that takes in account the condensed water beyond the snowline.

From Weidenschilling (1980) σ_o =10.2 g cm^{-2} and σ = 2.58 g cm^{-2} at r=5.2 AU. We took F=3 at this r. We computed the mass of a ring of nebula with inner and outer radius 5 AU and 5.4 AU, multiplied by 55/200 in order to take the Trojan survivors for 100 Myr. We get then an initial mass of Trojans of

$2.1x10^{27}$g. From which we get an accreted mass of $5.0x10^{23}$g. This value is of the order of the current mass of the Trojans, estimated by Jewitt et al. (2000) in $5x10^{23}$g.
The accreted mass seems to be too high, we think that due to the influence of the particle No. 13, which had 97 encounters with the Earth and a very long period maintaining q<1 AU, which led to a very high value of its individual collision probability, and weighted too much in a sample of 25 particles. If we assume that 2/3 of the bulk mass in Trojans is water, we get $3.3x10^{23}$g for the water accreted by the Earth. The amount of water that must have been supplied to the Earth is about $3x10^{24}$g (Morbidelli et al. 2000). From our results, we then conclude that the Trojan asteroids could have supplied 11% of the Earth's water.

IV.2 Evolution of the Second Sample

* In 100 Myr from the 250 initial particles 24 collided, three with the Sun, one with Saturn and the remaining ones with Jupiter. Other 102 particles were ejected from the system, mainly by the action of Jupiter.
* The Earth had 76 encounters with 13 particles, which were the three ones that finally collided with the sun, and ten that were later ejected by Jupiter.

We present below some properties that we had noted.
All the asteroids which collided with the sun, previously had encounters with the Earth. The parameter of Tisserand calculated for the system Sun–Jupiter becomes less than 3 in these bodies. (see figure 4)
None of the particles that collided with Jupiter have encounters with the Earth.
The parameter of Tisserand calculated for some of these bodies get values of a little less than 3.

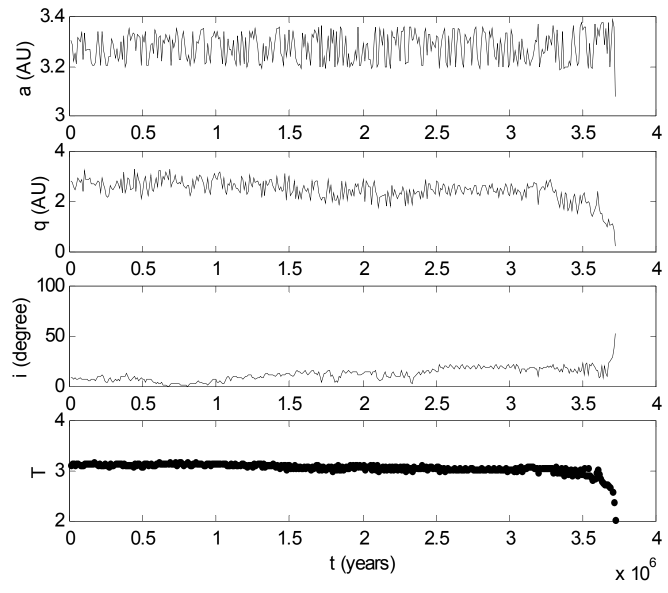

Fig 4 Evolution of orbital elements of particle No. 124 that collided with the Sun after to have 5 encounters with the Earth

Other Earth encounters are with asteroids which were ejected from the system. These bodies also reduce the parameter of Tisserand that is why the probability of collision with Jupiter is diminished. (Fernández 1999)

$$T = \frac{1}{a} + 2\sqrt{2q(1-\frac{q}{2a})}\cos i$$

in which a and q are in units of semimajor axis of Jupiter.
The Tisserand parameter is related to the encounter velocity by

$$U = \sqrt{3-T}$$

Between 40 Myr and 93 Myr, 11 particles were lost. We find two of these which had for some time q<1 AU, so the probability of collision with the Earth is not null. The collision probability was also preliminarily determined, yielding:
P=1.065x10^{-4}.
In order of estimate the initial mass in the outer main belt of asteroids, we computed the mass of a ring of nebula with inner and outer radii 3 AU and 4.5 AU, by taking values of F between 1.1 at r=3 AU and 2.6 at r=4.5 AU. We after multiplied by 120/250 in order to take the asteroids survivors for 100 Myr. From an initial mass of 2x10^{28}g we get an accreted mass of 2.1x10^{24} g. We took now 0.35 of the bulk mass as water in these bodies, and get 7.5x10^{23}g for the mass of accreted water. According to our preliminary results the outer main belt could have supplied 25% of the seawater.

V. CONCLUSIONS

In both samples we found that some particles which have stable orbits during some ten million years or so finally get away and some of them have trajectories of encounter with the Earth. Our preliminary results show that both types of bodies, Trojans and asteroids of the outer main belt could have substantially contributed to the supply of seawater on timescales that easily cover the formation time of Earth. We need more computing work to be able to know the probabilities of collision of these bodies with Earth with more confidence. This work is now in progress.

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