

Calculation of the enrichment of the giant planets envelopes during the “late heavy bombardment”

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Abstract

The giant planets of our solar system possess envelopes consisting mainly of hydrogen and helium but are also significantly enriched in heavier elements relatively to our Sun. In order to better constrain how these heavy elements have been delivered, we quantify the amount accreted during the so-called “late heavy bombardment”, at a time when planets were fully formed and planetesimals could not sink deep into the planets. On the basis of the “Nice model”, we obtain accreted masses (in terrestrial units) equal to $0.15 \pm 0.04 M_{\oplus}$ for Jupiter, and $0.08 \pm 0.01 M_{\oplus}$ for Saturn. For the two other giant planets, the results are found to depend mostly on whether

they switched position during the instability phase. For Uranus, the accreted mass is $0.051 \pm 0.003 M_{\oplus}$ with an inversion and $0.030 \pm 0.001 M_{\oplus}$ without an inversion. Neptune accretes $0.048 \pm 0.015 M_{\oplus}$ in models in which it is initially closer to the Sun than Uranus, and $0.066 \pm 0.006 M_{\oplus}$ otherwise. With well-mixed envelopes, this corresponds to an increase in the enrichment over the solar value of 0.033 ± 0.001 and 0.074 ± 0.007 for Jupiter and Saturn, respectively. For the two other planets, we find the enrichments to be 2.1 ± 1.4 (w/ inversion) or 1.2 ± 0.7 (w/o inversion) for Uranus, and 2.0 ± 1.2 (w/ inversion) or 2.7 ± 1.6 (w/o inversion) for Neptune. This is clearly insufficient to explain the inferred enrichments of ~ 4 for Jupiter, ~ 7 for Saturn and ~ 45 for Uranus and Neptune.

Key words: giant planets, planet formation, Jupiter, Saturn, Uranus, Neptune

1 Introduction

The four giant planets of our solar system have hydrogen and helium envelopes which are enriched in heavy elements with respect to the solar composition. In Jupiter, for which precise measurements from the Galileo probe are available, C, N, S, Ar, Kr, Xe are all found to be enriched compared to the solar value by factors 2 to 4 (Owen et al., 1999; Wong et al., 2004) (Assuming solar abundances based on the compilation by Lodders (2003)). In Saturn, the C/H ratio is found to be 7.4 ± 1.7 times solar (Flasar et al., 2005). In Uranus and Neptune it is approximately 45 ± 20 times solar (Guillot and Gautier, 2007)

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10 (corresponding to about 30 times solar with the old solar abundances). In-
11 terior models fitting the measured gravitational fields constrain enrichments
12 to be between 1.5 and 8 for Jupiter and between 1.5 and 7 times the solar
13 value for Saturn (Saumon and Guillot, 2004). For Uranus and Neptune, the
14 envelopes are not massive enough (1 to 4 Earth masses) for interior models to
15 provide global constraints on their compositions.

16 Enriching giant planets in heavy elements is not straightforward. Guillot and
17 Gladman (2000) have shown that once the planets have their final masses, the
18 ability of Jupiter to eject planetesimals severely limits the fraction that can
19 be accreted by any planet in the system. The explanations put forward then
20 generally imply an early enrichment mechanism:

- 22 • Alibert et al. (2005) show that migrating protoplanets can have access to
23 a relatively large reservoir of planetesimals and accrete them in an early
24 phase before they have reached their final masses and started their contrac-
25 tion. This requires the elements to be mixed upward efficiently, which is
26 energetically possible, and may even lead to an erosion of Jupiter's central
27 core (Guillot et al., 2004).
- 28 • The forming giant planets may accrete a gas that has been enriched in heavy
29 elements through the photoevaporation of the protoplanetary disk's atmo-
30 sphere, mainly made of hydrogen and helium (Guillot and Hueso, 2006).
31 This could explain the budget in noble gases seen in Jupiter's atmosphere
32 but is not sufficient to explain the enrichment in elements such as C, N,
33 O because small grains are prevented from reaching the planet due to the
34 formation of a dust-free gap (eg. Paardekooper, 2007). The photoevapo-
35 ration model requires that the giant planets form late in the evolution of

36 disks, which appears consistent with modern scenarios of planet formation
37 (see Ida and Lin (2004); Ida et al. (2008)). It also implies that a significant
38 amount of solids are retained in the disk up to these late stages, as plausible
39 from simulations of disk evolution (e.g. Garaud (2007)).

40 It has been recently suggested that the Solar System underwent a major
41 change of structure during the phase called ‘Late Heavy Bombardment’ (LHB)
42 (Tsiganis et al., 2005; Gomes et al., 2005). This phase, which occurred \sim
43 650 My after planet formation, was characterized by a spike in the cratering
44 history of the terrestrial planets.

45 The model that describes these structural changes, often called the ‘Nice
46 model’ because it was developed in the city of Nice, reproduces most of the
47 current orbital characteristics of both planets and small bodies. This model
48 provides relatively tight constraints on both the location of the planets and on
49 the position and mass of the planetesimal disk at the time of the disappear-
50 ance of the proto-planetary nebula. Thus, it is interesting to study the amount
51 of mass accreted by the planets at the time of the LHB, in the framework of
52 this model.

53 The article is organized as follows: we first describe the orbital evolution model
54 at the base of the calculation. Physical radii of the giant planets at the time
55 of the late heavy bombardment are also discussed. We then present results,
56 both in terms of a global enrichment and in the unlikely case of an imperfect
57 mixing of the giant planets envelopes.

58 **2 The ‘Nice’ model of the LHB**

59 *2.1 General description*

60 The Nice model postulates that the ratio of the orbital periods of Saturn and
61 Jupiter was initially slightly less than 2, so that the planets were close to
62 their mutual 1:2 mean motion resonance (MMR); Uranus and Neptune were
63 supposedly orbiting the Sun a few AUs beyond the gas giants, and a massive
64 planetesimal disk was extending from 15.5 AU, that is about 1.5 AU beyond
65 the last planet, up to 30–35 AU.

66 As a consequence of the interaction of the planets with the planetesimal disk,
67 the giant planets suffered orbital migration, which slowly increased their or-
68 bital separation. As shown in Gomes et al. (2005) N-body simulations, after a
69 long quiescent phase (with a duration varying from 300 My to 1 Gy, depend-
70 ing on the exact initial conditions), Jupiter and Saturn were forced to cross
71 their mutual 1:2 MMR. This event excited their orbital eccentricities to values
72 similar to those presently observed.

73 The acquisition of eccentricity by both gas giants destabilized Uranus and
74 Neptune. Their orbits became very eccentric, so that they penetrated deep
75 into the planetesimal disk. Thus, the planetesimal disk was dispersed, and the
76 interaction between planets and planetesimals finally parked all four planets
77 on orbits with separations, eccentricities and inclinations similar to what we
78 currently observe.

79 This model has a long list of successes. It explains the current orbital archi-
80 tecture of the giant planets (Tsiganis et al., 2005). It also explains the origin
81 and the properties of the LHB. In the Nice model, the LHB is triggered by

82 the dispersion of the planetesimal disk; both the timing, the duration and the
83 intensity of the LHB deduced from Lunar constraints are well reproduced by
84 the model (Gomes et al., 2005).

85 Furthermore, the Nice model also explains the capture of planetesimals around
86 the Lagrangian points of Jupiter, with a total mass and orbital distribution
87 consistent with the observed Jupiter Trojans (Morbidelli et al., 2005). More
88 recently, it has been shown to provide a framework for understanding the cap-
89 ture and orbital distribution of the irregular satellites of Saturn, Uranus and
90 Neptune, but not of Jupiter (Nesvorný et al., 2007), except in the case of an
91 encounter between Jupiter and Neptune which is a rare but not impossible
92 event. The main properties of the Kuiper belt (the relic of the primitive trans-
93 planetary planetesimal disk) have also been explained in the context of the
94 Nice model (Levison et al. (2008); see Morbidelli et al. (2008), for a review).

95 *2.2 The dynamical simulations*

96 In this work, we use 5 of the numerical simulations performed in (Gomes et al.,
97 2005). The main simulation is the one illustrated in the figures of the Gomes
98 et al. paper. The 1:2 MMR crossing between Jupiter and Saturn occurs after
99 880 My, relatively close to the observed timing of the LHB (650 My). When
100 the instability occurs, the disk of planetesimals still contained 24 of its initial
101 35 Earth masses (M_{\oplus}).

102 During the evolution that followed the resonance crossing, Uranus and Nep-
103 ture switched position. Thus, according to this simulation, the planet that
104 ended up at ~ 30 AU (Neptune) had to form closer to the Sun than the
105 planet that reached a final orbit at ~ 20 AU (Uranus).

106 However, because the planets evolutions are chaotic during the instability
107 phase, different outcomes can be possible. Thus Gomes et al. performed 4
108 additional simulations with initial conditions taken from the state of the sys-
109 tem in the main simulation just before the 1:2 resonance crossing, with slight
110 changes in the planets' velocities. Two of these 'cloned' simulations again
111 showed a switch in positions between Uranus and Neptune, but the two oth-
112 ers did not. That is, in these two cases the planet that terminated its evolution
113 at 30 AU also started the furthest from the Sun.

114 Here we use these 5 simulations (the main one and its 4 'clones') to evaluate
115 the amount of solid material accreted by the planets and how it could vary
116 depending on the specific evolutions of the ice giants. Notice that, whereas the
117 main simulation spans 1.2 Gy (and therefore continues for 320 My after the
118 1:2 MMR crossing), the cloned simulations cover only a time-span of approx-
119 imately 20 My, and were stopped when the planets reached well separated,
120 relatively stable orbits.

121 *2.3 Probability of impact and accretion of planetesimals*

122 From these dynamical simulations, several steps are necessary to estimate the
123 amount of mass accreted by the planets.

124 For each simulation at each output time (every 1 My) we have the orbital
125 elements of the planets and of all the planetesimals in the system. We are
126 aware that this time interval may be a bit too long to resolve the evolution
127 of the system during the transient phases that immediately follow the onset
128 of the planetary instability. On the other hand, when the instability occurs,
129 most of the disk is still located beyond the orbits of the planet, so that the

130 bombardment rate is not very high. Thus, we believe that this coarse time
 131 sampling is enough for our purposes.

132 First we look for planetesimals that are in a mean motion resonance with a
 133 planet. The resonances taken into account are the 1:1, 1:2, 2:3, 2:1, 3:2. When
 134 computing the collision probability with a planet, the objects in resonance
 135 with that planet will not be taken into account (but they will be considered
 136 for the collision probability with the other planets). The rationale for this
 137 is that the resonant objects, even if planet-crosser, cannot collide with the
 138 planet, because they are phase-protected by the resonant configuration, as in
 139 the case of Pluto.

140 The width of a resonance is proportionnal to $\sqrt{\frac{M_{\text{planet}}}{M_{\text{sun}}}} * a$ where M_{planet} is
 141 the mass of the considered planet and a is the semi-major axis of the precise
 142 resonant orbit. Hence we take an approximative relative width of $\frac{\Delta a}{a} = 1\%$ on
 143 the semi-major axis to define the area where a planet and a given planetesimal
 144 are considered to be in resonance. Then we select all the non-resonant particles
 145 that cross the orbit of a planet. The intrinsic collision probability P_i of each
 146 of these particles with the planet is computed using the method detailed in
 147 Wetherill (1967), implemented in a code developed by Farinella et al. (1992)
 148 and kindly provided to us. Once P_i is known for each particle ($i = 1, \dots, N$),
 149 the mass accreted by the planet during the time-step Δt is simply :

$$150 \quad M_{acc} = \sum_{i=1}^N P_i R_{\text{planet}}^2 M_i \Delta t f_{grav} \quad (1)$$

151 where M_i is the mass of the planetesimal (with $M_i = 0.00349$ Earth mass),
 152 and f_{grav} is the gravitational focusing factor. The latter is equal to :

$$153 \quad f_{grav} = 1 + \frac{V_{\text{lib}}^2}{V_{\text{rel}}^2} \quad (2)$$

154 where V_{rel} is the relative velocity between the planet and the planetesimal, and
155 V_{lib} is the escape velocity from the planet. Finally, the total mass accreted by
156 a planet during the full dynamical evolution is simply the sum of M_{acc} over
157 all time-steps taken in the simulation.

158 **3 Results: mass accreted by each giant planets**

159 Fig.1 shows the cumulated mass captured by Jupiter, Saturn, Uranus and
160 Neptune as a function of time in the case of the main simulation. The abrupt
161 increase at 882 Ma is due to the triggering of the LHB when Saturn crosses
162 the 1:2 resonance with Jupiter. It is interesting to notice that this short phase
163 accounts for about two third of the mass acquired by the planets during their
164 full evolution.

165 Qualitatively, the more massive is the planet, the larger is the mass accreted
166 from the planetesimal disk. This is because larger planets have larger gravita-
167 tional cross sections.

168 Uranus and Neptune have comparable masses, and therefore which planets
169 accretes more mass depends on their orbital histories. In the model shown
170 in Fig.1, Uranus first accretes planetesimals at a larger rate than Neptune
171 because Uranus is initially the furthest planet in the system and the closest
172 to the planetesimal disk. However, when the two planets exchange position
173 and Neptune is scattered into the planetesimal disk, it accretes many more
174 planetesimals and eventually exceeds Uranus in terms of total accreted mass.
175 As previously described, the evolution of the system is very chaotic and Fig.1
176 only represents one of the possible outcomes. In order to assess the variability
177 of the solutions, we also present in Fig.2 the evolution of the 4 "cloned" sim-

178 ulations focused around the critical period of the 1:2 MMR crossing. We note
 179 them 'simu *a*', 'simu *b*', 'simu *c*', and 'simu *d*'. These simulations were started
 180 at 868 Myr, just before the 1:2 MMR crossing (≈ 880 Myr), and stopped at
 181 893, 897, 875 and 899 Myr respectively, as soon as the planets reached well
 182 separated and relatively stable orbits.

183 Fig.2 shows that the variability of the accreted masses during that period
 184 amounts to up to a factor 2 for all planets except Neptune, for which the
 185 variability is a factor 4. The added uncertainty on the results due to the 1
 186 Myr timestep appears small in comparison, as shown by the regularity of the
 187 curves.

188 In order to obtain the evolution of the mass accreted by 4 giant planets during
 189 the entire 1.2 Gyr period and to assess the effect of the position switch be-
 190 tween Uranus and Neptune on the final accreted mass, we proceed as follows:
 191 we simply assume that the planets accreted the same amount of mass as in
 192 the main simulation over the first 880 Myr and over the time ranging from the
 193 end of each cloned simulation up to 1,200 Myr. In the cases in which Uranus
 194 and Neptune do not switch positions, we consider that Uranus accreted before
 195 the LHB the same mass accreted by "Neptune" (the 4th planet) in the main
 196 simulation, and inversely for Neptune. The results are shown in Fig. 3. We
 197 can see that the results for simulations are very similar to the result for the
 198 main simulation. However in the simulation *a*, Neptune eventually accretes
 199 less mass than Uranus. Conversely, the results for the simulations *b* and *d* are
 200 qualitatively different. Neptune is initially the closest planet to the disk and
 201 hence accretes much more planetesimals than Uranus also before the LHB.
 202 This remains the case during/after the LHB, since Neptune is scattered into
 203 the disk and acquires even more planetesimals compared to Uranus.

204 Table 1 summarizes the total masses accreted by the planets, and compares

205 them to the masses of heavy elements in their hydrogen-helium envelopes es-
 206 timated from interior models fitting the giant planets gravitational moments
 207 (see Guillot, 2005). As before, for Uranus and Neptune, we separate the cases
 208 in which these planets exchange their positions from the cases in which they
 209 do not.

210 In the first case, Uranus accretes an amount of planetesimals comparable to
 211 Neptune's, whereas when the order of the ice giants is not switched, Neptune
 212 accretes twice more planetesimals than Uranus. In all cases, the masses ac-
 213 creted are significantly smaller than the masses of the envelopes.

214 For Jupiter and Saturn, the mass accreted is much lower ($\approx 10^{-3}$ times
 215 smaller), whereas this ratio can increase to $\sim 7 \times 10^{-2}$ for Uranus and Nep-
 216 tune. Therefore in the framework of the 'Nice' model, the LHB has a stronger
 217 impact in terms of heavy elements supply relatively to the envelope mass, in
 218 the case of the two latter planets, Uranus and Neptune.

219 4 Calculation of the envelope enrichments

220 4.1 Fully mixed case

221 Once we calculated the mass that each planet accreted during this period,
 222 it is straightforward to infer the corresponding change in composition. We
 223 thus calculate the increase of the atmosphere's enrichment $\Delta\mathcal{E}$, defined as the
 224 amount of heavy elements for a given mass of atmosphere compared to that
 225 same value in the Sun. More specifically, the global enrichment increase of
 226 a giant planet envelope of mass M_{envelope} accreting a mass of planetesimals

227 M_{accreted} (assuming that planetesimals don't reach the core) is:

$$228 \quad \Delta\mathcal{E}_{\text{LHB}} = \frac{M_{\text{accreted}}}{M_{\text{envelope}} \times Z_{\odot}} \quad (3)$$

229 where Z_{\odot} is the mass fraction of heavy elements in the Sun. Following Grevesse
230 et al. (2005), we use in mean $Z_{\odot} = 0.015$. This global enrichment is also the en-
231 richment of the atmosphere, provided the envelope is well-mixed, a reasonable
232 assumption given the fact that these planets should be mostly convective (see
233 e.g. Guillot, 2005). These values of enrichment are calculated by taking the
234 mean of the accreted masses of the table 1, and the uncertainty on the enve-
235 lope mass is taken into account. Table 2 shows that this yields relatively small
236 enrichments: the contribution of this late veneer of planetesimals accounts for
237 only about 1% of the total enrichments of Jupiter and Saturn, and up to 10%
238 in the case of Uranus and Neptune, owing to their smaller envelopes.

239 *4.2 Incomplete mixing case*

240 Mixing in the envelopes of giant planets is expected to be fast compared to the
241 evolution timescales, and rather complete because these planets are expected
242 to be fully convective (Guillot, 2005). We want to test the possibility, however
243 unlikely, that mixing was not complete, and that the observed atmospheric
244 enrichments were indeed caused by these late impacts of planetesimals.

245 The values of enrichment, in the hypothesis of an incomplete mixing of the
246 envelope, depends on two elements : the extent of mixing of heavy elements in
247 the envelope, but also the penetration depth of planetesimals in the envelope
248 as a function of their size distribution at the time of the LHB.

249 First let us evaluate to what extent the mixing should occur in order to retrieve

250 the observed enrichments ($\mathcal{E}_{C/H}$ in Table 2). Following Eq.3, we evaluate the
 251 mass of envelope over which planetesimals should penetrate and be mixed to
 252 explain the observations :

$$253 \quad M_{\text{mixed}} = \frac{M_{\text{accreted}}}{\mathcal{E}_{C/H} \times Z_{\odot}} \quad (4)$$

254 Using hydrostatic balance, and assuming a constant adiabatic gradient of 0.3, a
 255 pressure of 1 bar at the top of the atmosphere and a gravitational acceleration
 256 constant and equal to its value at the top of the atmosphere, we calculate the
 257 corresponding penetration depth, h_{mixed} , and pressure, P_{mixed} , at this depth .

258 We now have to consider in addition the penetration depth of planetesimals
 259 in the envelope as a function of their size distribution at the time of the LHB.

260 The reason is that, even if we could define the extents of penetration and
 261 mixing giving the observed enrichments, an important fraction of planetesi-
 262 mals penetrating more deeply in the envelope would anyway cause a heavy
 263 elements supply over a larger extent, implying atmospheric enrichments lower
 264 than those observed.

265 We thus have to determine the mass of the envelope shell enriched by a plan-
 266 etesimal of a given size. The main assumption here is to consider that during
 267 its entry into the atmosphere, the planetesimal desintegrates and mixes com-
 268 pletely with the atmosphere after crossing a mass of gas column equal to its
 269 own mass. Thanks to a parallel plane approximation of the atmosphere, the
 270 mass of the atmospheric shell thus enriched can be inferred from the ratio
 271 between the planetary area a_{planet} and the planetesimal section a_{pl} multiplied
 272 by the mass of the considered planetesimal M_{pl} :

$$273 \quad M_{\text{enriched shell}} = M_{\text{pl}} \frac{a_{\text{planet}}}{a_{\text{pl}}} \quad (5)$$

274 We now define s_{mixed} , the critical planetesimal radius for which $M_{\text{enriched shell}} =$
 275 M_{mixed} . Following Equations 5 and 6 and considering ice spherical planetesi-
 276 mals with a mass density noted ρ :

$$277 \quad s_{\text{mixed}} = \frac{3 \times M_{\text{mixed}}}{4 \times a_{\text{planet}} \times \rho} \quad (6)$$

278 All the planetesimals larger than s_{mixed} will penetrate more deeply than the
 279 extent of mixing and will enrich a larger part of the envelope, yielding the
 280 enrichments lower than observed.

281 We now evaluate the mass fraction of planetesimals with sizes larger than
 282 s_{mixed} . For that we use a bi-modal size distribution inspired from the observa-
 283 tions of Trans-Neptunian Bodies (Bernstein et al., 2004), and used successfully
 284 by Charnoz and Morbidelli (2007) to explain the number of comets in the scat-
 285 tered disk and the Oort cloud :

$$286 \quad \frac{dN}{ds} = f_{\text{small}} \times s^{-3.5} \quad s < s_0 \quad (7)$$

$$287 \quad \frac{dN}{ds} = f_{\text{big}} \times s^{-4.5} \quad s > s_0 \quad (8)$$

288 with $50\text{km} < s_0 < 100\text{km}$ the turnover radius, and f_{small} and f_{big} the nor-
 289 malisation factors which depends on the value of s_0 and the total mass of the
 290 planetesimals disk (Gomes et al., 2005). For each planet, the mass fraction is
 291 calculated with $s_0=50$ and 100 km in order to have a good range of values
 292 around the estimated one which is approximately 70 km according to Fuentes
 293 and Holman (2008).

294 Table 3 summarizes the results obtained in the case of an incomplete mixing.
 295 Compared to the whole envelope mass, the masses of layer enriched by this
 296 incomplete mixing are of the order of 1% for Jupiter and Saturn, and between

297 5 and 10% for Uranus and Neptune. As previously mentioned, these values and
298 those of the related quantities are a priori unrealistic because of the globally
299 convective structure of the giant planets. Moreover, according to the results of
300 mass fraction in Table 3, we see that the large planetesimals with a size bigger
301 than s_{mixed} are comparable and even predominant in terms of mass compared
302 to the small ones, especially for Uranus and Neptune.

303 Therefore even if we assume an incomplete mixing giving the observed en-
304 richments, the important supply of heavy elements by the large planetesimals
305 at layers deeper than h_{mixed} will imply anyway lower enrichments than those
306 observed.

307 In summary, it appears that the observed enrichments cannot be explained in
308 the context of the Late Heavy Bombardment even by using the hypothesis of
309 an incomplete mixing.

310 5 Conclusion

311 In this work, we evaluated the extent to which the late heavy bombardment
312 could explain the observed enrichments of giant planets.

313 We calculated the mass accreted by each planet during this period thanks to
314 several dynamical simulations of the LHB within the so-called "Nice" model.

315 The accreted masses were found to be much smaller than those of the en-
316 velopes of each giant planet. In the realistic hypothesis of a global mixing in
317 these envelopes, we found the enrichments over the solar value to be approxi-
318 mately two orders of magnitude smaller than the observations for Jupiter and
319 Saturn and one order of magnitude smaller than the observations for Uranus
320 and Neptune.

321 We then tested the possibility of an incomplete mixing in the giant planets
322 envelopes to account for the observed enrichments. With a size distribution of
323 planetesimals inferred from observations of trans-neptunian bodies, we found
324 that the enrichments were always at least a factor of 2 lower than observed.
325 Given the efficient convection expected in the deep atmosphere, we expect
326 however the mixing to be complete.

327 Therefore we conclude that the enriched atmospheres of the giant planets do
328 not result from the Nice model of the LHB and probably from any model de-
329 scribing the LHB. In fact Guillot and Gladman (2000)'s calculations showed
330 that the mass needed to explain Jupiter's and Saturn's enrichments would
331 be certainly much too large, in any late heavy bombardment model. Earlier
332 events should thus be invoked in the explanation of the enriched atmospheres
333 of giant planets. On the other hand the enrichment process during the LHB
334 may not be completely negligible when considering fine measurements of the
335 compositions of giant planets (eg. Marty et al., 2008). When present it may
336 also have a role in enriching the envelopes of close-in extrasolar giant planets
337 because of their radiative structure.

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435 Caption figure 1 : Mass accreted (in Earth mass units) by Jupiter (plain),
436 Saturn (dashed), Uranus (dash-dotted) and Neptune (dotted) respectively, as
437 a function of time (in years). The simulation corresponds to the main simula-
438 tion described in the text, in which Uranus and Neptune switch their relative
439 positions.

440 caption figure 2 : Additional mass accreted (in Earth mass units) during the
441 time range of the 4 'cloned' simulations. Figures a and c (left) correspond
442 to the cases in which Uranus and Neptune exchange position at the time of
443 the LHB. Figures b and d (right) show the result of simulations in which the
444 four planets preserve their initial order. These 'cloned' simulations start 868
445 Myr after the beginning of the planets migration and are stopped once giant
446 planets acquired well separated and stable orbits.

447 Caption figure 3 : Mass accreted(in Earth mass units) for the 4 'cloned' sim-
448 ulations during the whole time scale of the 'Nice' model. In each of these four
449 panels, the period before 868 Myr and after 875-899 Myr (depending on the
450 simulation) is assumed to be identical to the main simulation. Figures a and c

451 (left) correspond to the cases in which Uranus and Neptune exchange position
 452 at the time of the LHB. Figures b and d (right) show the result of simulations
 453 in which the four planets preserve their initial order.

454 Caption table 1 : Planetesimal masses accreted by the giant planets after the
 455 disappearance of the protosolar gaseous disk.

456 Caption table 2 : Enrichment increase (see equation 3) calculated from the
 457 different simulations of the model. The values of the observed $\epsilon_{C/H}$ are derived
 458 from Guillot (2005).

459 Caption table 3 : Mass of enriched layer, extent of mixing h_{mixed} , pressure
 460 level at the bottom of the mixing area P_{mixed} , and planetesimal radii s_{mixed} ,
 461 which would match the observed enrichments. The last column is the mass
 462 percentage corresponding to the planetesimals whose the radius is larger than
 463 s_{mixed} , the range being due to the two limiting values of s_0 used.

Fig. 1.

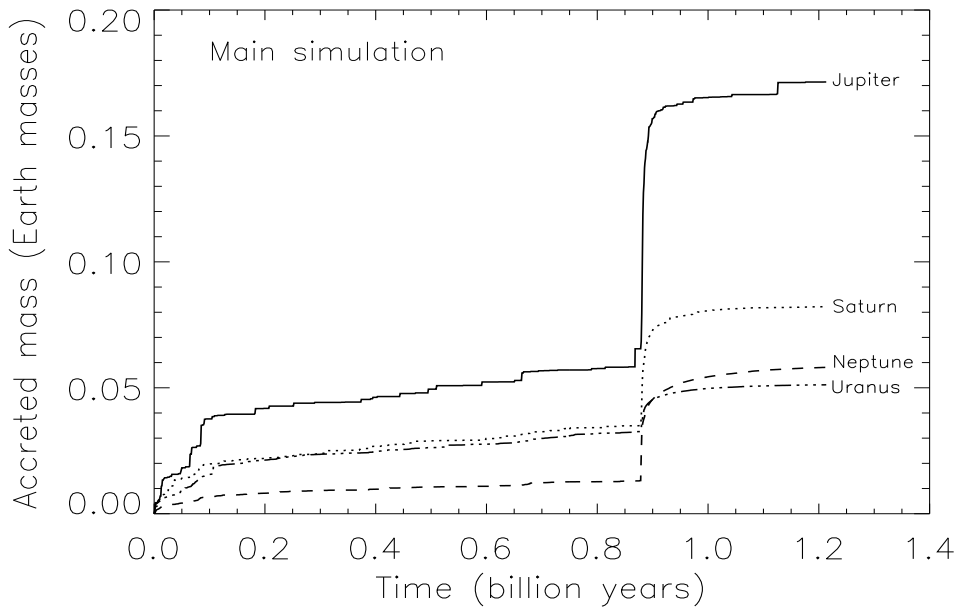


Fig. 2.

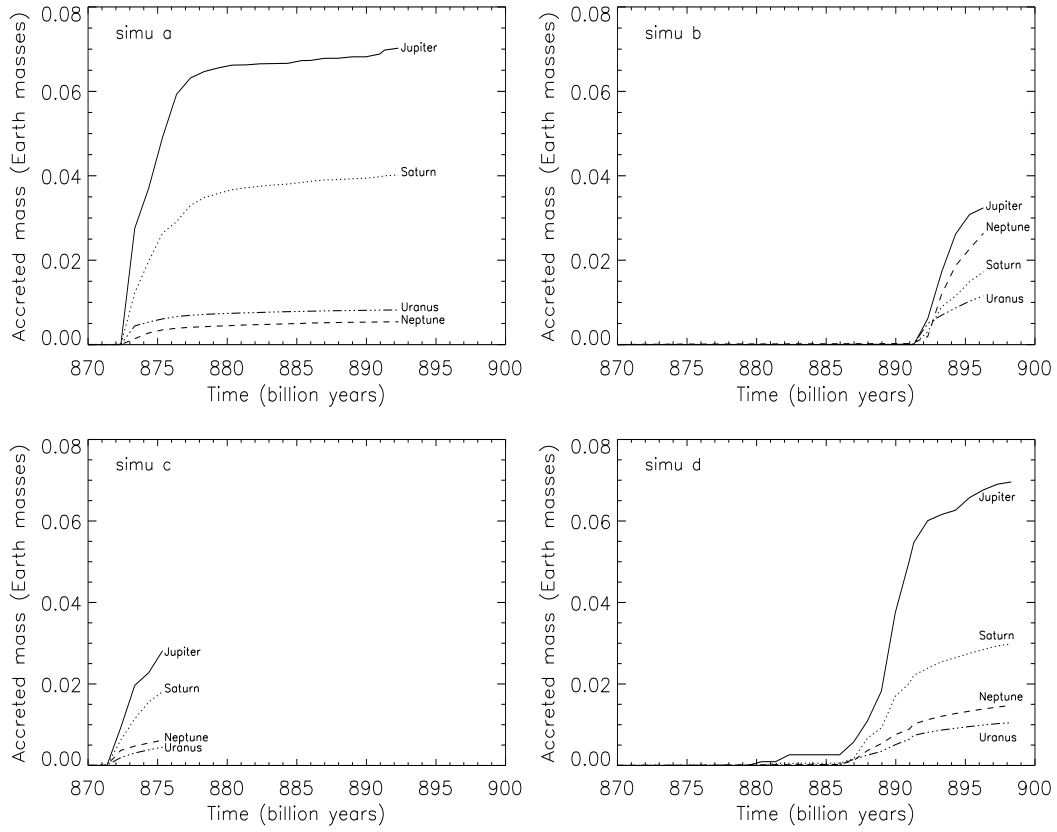


Table 1

<i>Giant planet</i>	<i>Envelope mass</i> [M_{\oplus}]	<i>Accreted mass</i> [M_{\oplus}]
Jupiter	300 – 318	0.11 – 0.20
Saturn	70 – 85	0.06 – 0.10
Uranus (w/ inversion)	1 – 4	0.048 – 0.055
(w/o inversion)		0.029 – 0.031
Neptune (w/ inversion)	1 – 4	0.033 – 0.064
(w/o inversion)		0.060 – 0.072

Fig. 3.

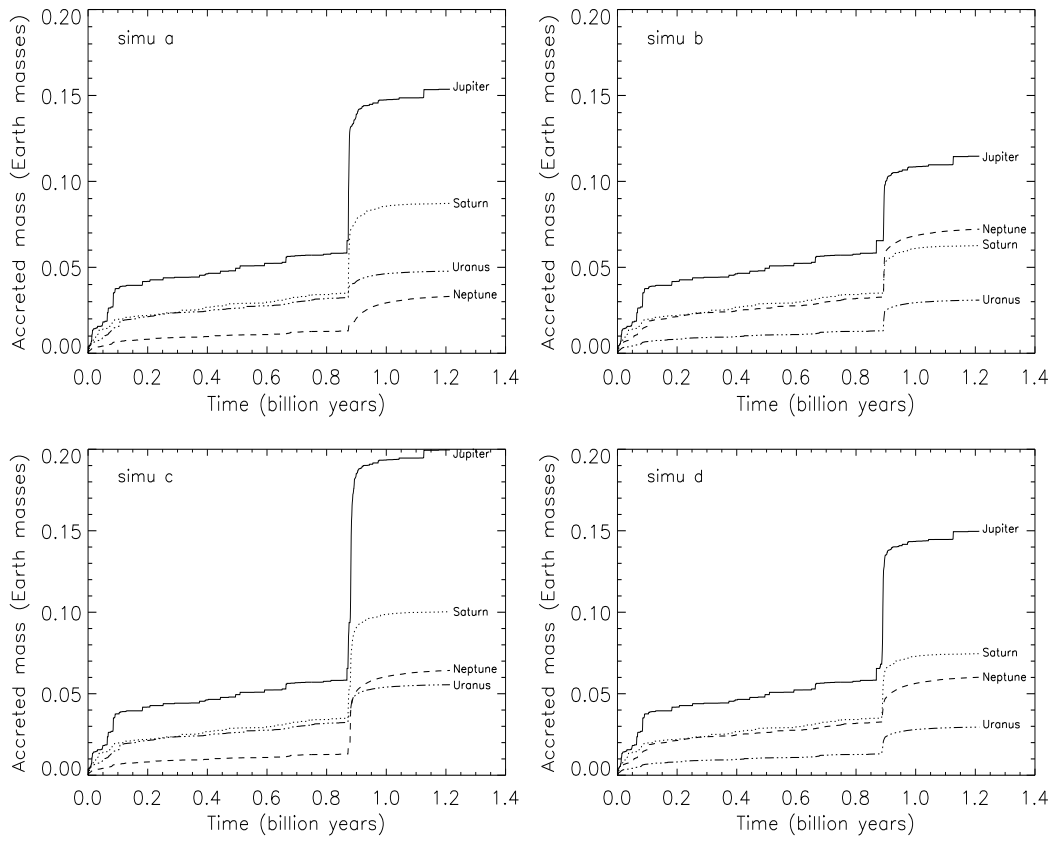


Table 2

<i>Giant planet</i>	$\Delta\epsilon_{\text{LHB}}$	<i>Observed</i> $\epsilon_{\text{C/H}}$
Jupiter	0.032-0.034	4.1 ± 1
Saturn	0.062-0.076	7.4 ± 1.7
Uranus (w/ inversion)	0.8 – 3.4	45 ± 20
(w/o inversion)	0.5 – 2	
Neptune (w/ inversion)	0.8-3.2	45 ± 20
(w/o inversion)	1.1-4.4	

Table 3

<i>Giant planet</i>	M_{mixed} (M_{\oplus})	h_{mixed} (km)	P_{mixed} (bar)	s_{mixed} (km)	% $M(s > s_{\text{mixed}})$
Jupiter	3.41	2000	48300	248	23%-32%
Saturn	0.82	2200	7200	86	39%-54%
Uranus (w/ inversion)	0.11	1200	4200	63	44%-60%
(w/o inversion)	0.07	1000	2500	37	57%-69%
Neptune (w/ inversion)	0.11	1000	5100	61	45%-61%
(w/o inversion)	0.15	1400	13100	84	39%-54%