The Nice model and dynamics of the Late Heavy Bombardment

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Two contrasting views of the timeline of the lunar bombardment:

1) An exponential decay, from the time of lunar formation

2) A prominent spike in the bombardment rate ~ 3.9Gy ago
Morbidelli et al., 2007; Levison et al., 2011
Multiple Solar System features give evidence for a Giant Planet Instability (i.e. THE NICE MODEL)

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But the timing of the instability is NOT constrained by the dynamics

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THE ORBITS OF THE GIANT PLANETS

Because in the protoplanetary disk Saturn migrates faster than Jupiter and Uranus and Neptune migrate faster than Jupiter & Saturn, the planets should have been caught in resonant by convergent migration (Morbidelli and Crida, 2007; Morbidelli et al., 2007)
THE ORBITS OF THE GIANT PLANETS

Statistics on Nice model outcomes (Nesvorny and Morbidelli, 2012)
Origin of the Irregular Satellites of the Giant Planets
Capture during Planetary Encounters

Captured Irregular Satellites
Autres implications du modèle: origine des satellites irréguliers des Saturne, Uranus et Neptune (Nesvorny et al., 2007)

The shallow SFD is explained by subsequent collisional evolution (Bottke et al., 2010)
Capture of Jupiter’s Trojans during Jupiter’s last encounter (Nesvorny et al., 2013)

This mechanism has the potential to explain the $L_4/L_5$ asymmetry.
The Nice model explains the existence, the structure and the small mass of the Kuiper belt (Nesvorny, 2016a,b)

Cold belt

![Simulated and Observed data comparison](image)

- Semimajor Axis (AU)
- Inclination (deg)
- Eccentricity

Hot belt

![Distribution of objects by eccentricity and inclination](image)

- Eccentricity
- Inclination (deg)
- N(＜e)
- N(＜i)

HCs
...and the formation of an Oort cloud with a total population consistent with the flux of LPCs (Brasser and Morbidelli, 2013)

- Observations of the fluxes of LPCs and JFCs suggest a OC/SD ratio of $44^{+54}_{-34}$ (Brasser and Morbidelli, 2013)
- The fact that the giant planet instability occurred after gas-removal explains why small comets could reach the Oort Cloud
So... the dynamics of the Nice model is compelling

But what about the timing of the instability?

Let’s go back to the Moon!!
The Giant Planet instability produces a flux of planetesimals/projectiles from the trans-Neptunian region and the asteroid belt to the inner Solar System.
Total number of projectiles from asteroid belt

Decay rate of projectile population

Timing of giant planet instability (unknown)

Morbidelli et al., 2012
Decay rate of planetesimals left-over from terrestrial planet accretion.
Total number of bodies impacting the Moon since its formation (known from HSE abundance in the lunar mantle/crust ($1.7 \times 10^{19}$ kg Day et al., 2010) and projectile SFD).
Crater count data for lunar terrains with radiometric ages.
Best fit solution

Instability at ~4.1 Gy

Morbidelli et al., 2012
A reanalysis with new asteroid simulations (Nesvorny et al., 2017) and including comets. Role of comets at odds with chemical analyses of impact clasts (Kring and Cohen, 2002).

The HSE concentration may not be diagnostic of the mass accreted since Moon formation (Rubie et al., 2016).

Sequestration of HSEs due to FeS exsolution during magma ocean crystallization
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• The depletion of HSEs from the upper mantle occurs when the latter crystallizes
• HSE concentration tracks just the material accreted since the crystallization of the upper magma ocean
• The latter may have occurred 100-200My after Moon formation (Elkins-Tanton et al., 2011)
This curve can be scaled up

HSE “constraint”
The lunar late heavy bombardment as a tail-end of planet accretion

- Implies crystallization of magma ocean at 4.35Gy, within the range of Elkins-Tanton et al. (2011) and in agreement with the ages of the oldest rocks (Borg et al., 2011)
- Allows the Moon to accrete $\sim 1/20$ of 0.1% of an Earth mass. No need to invoke giant projectiles as in Bottke et al., 2012

CONCLUSIONS

• No need of a late instability to explain the Late Heavy Bombardment
• It is enough that the lunar magma ocean solidified late, in agreement with lunar thermal evolution models and rock ages. Not certain but plausible

This model is much simpler than the late instability model
• No need to invoke an ad-hoc projectile SFD to explain the imbalance in HSE content between the Earth and the Moon
• No need of fine tuning in the dynamical models to get a late instability
• No issues with crater count son Pluto and Charon
• No contribution of comets in the LHB

But:
• The Moon received 10x more basin-forming impacts than the actual number of basins observed.
• Needs to retain craters/basins only since ~4.35-4.40 Gy ago
• The crust was too warm and its viscosity too low to retain early impact structures?
CONCLUSIONS

- No need of a late instability to explain the Late Heavy Bombardment
- It is enough that the lunar magma ocean solidified late, in agreement with lunar thermal evolution models and rock ages.
- This model is much simpler than the late instability model
- No need to invoke a weird projectile SFD to explain the imbalance in HSE content between the Earth and the Moon
- No need of fine tuning in the dynamical models to get a late instability
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- No contribution of comets in the LHB
Role of asteroids and comets if the LHB was due to a late instability. At odds with chemical analyses of impact clasts (Kring and Cohen, 2002).
Is this kind of dynamics compatible with a delayed instability? Deienno et al. in prep.
If $\delta < \delta_{\text{mig}}$, Neptune has long-range planetesimal driven migration.
If $\delta > \delta_{\text{stab}}$, the planetary system is stable.

IDEA: the dust produced in the planetesimal disk by mutual collision, flowing towards the Sun by PR drag, can move Neptune slowly, so that $\delta$ changes from $> \delta_{\text{stab}}$ to $< \delta_{\text{mig}}$ in a long time.
Figure 3. Evolution of Neptune’s semimajor axis under the effects of the dust flux ($\phi_{dust}$), as a function of the time. From bottom to top: light gray represents the evolution for $\phi_{dust}^1 = 1 \, M_\oplus$ per 400 My, black for $\phi_{dust}^{10} = 10 \, M_\oplus$ per 400 My, and dark gray for $\phi_{dust}^{20} = 20 \, M_\oplus$ per 400 My. The straight lines, from bottom to top, represent one possible linear fit to these evolutions (dashed black for $\phi_{dust}^1$, white for $\phi_{dust}^{10}$, and solid black for $\phi_{dust}^{20}$).
A late instability is possible, but it requires some intelligent design: disk distance, disk mass, dust production (function of planetesimal SFD and orbital excitation).

A model that does not require this, as the new model of early instability and late Lunar cooling is preferable.