The impact rate on giant planet satellites during the Late Heavy Bombardment in the Nice 2 Model

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What is the Nice model?

The Nice model is a set of theories in which the orbits of the giant planets, particularly Uranus and Neptune, changed long after the planets formed. This planetary rearrangement ("instability") unleashed a flood of comets and asteroids throughout the Solar System. Our goal was to determine the mass in comets that struck the regular moons of Jupiter, Saturn, Uranus, and Neptune.

The Nice model comes in three flavors.
• **Classic** (Tsiganis et al. 2005, Morbidelli et al. 2005, Gomes et al. 2005; **Figure 1**): Jupiter and Saturn cross 2:1 resonance; chaos ensues.
• **Nice 2** (Levison et al. 2011): **More realistic initial conditions than classic Nice model**. Jupiter, Saturn, Uranus, and Neptune start in resonance with each other. "Plutos" destabilize planetesimal disk; chaos ensues.
• **Hipster** (Nesvorný 2011, Batygin et al. 2012, Nesvorný and Morbidelli 2012, 2013): The Solar System used to have one or two more giant planets. You've probably never heard of them. Chaos ensues.

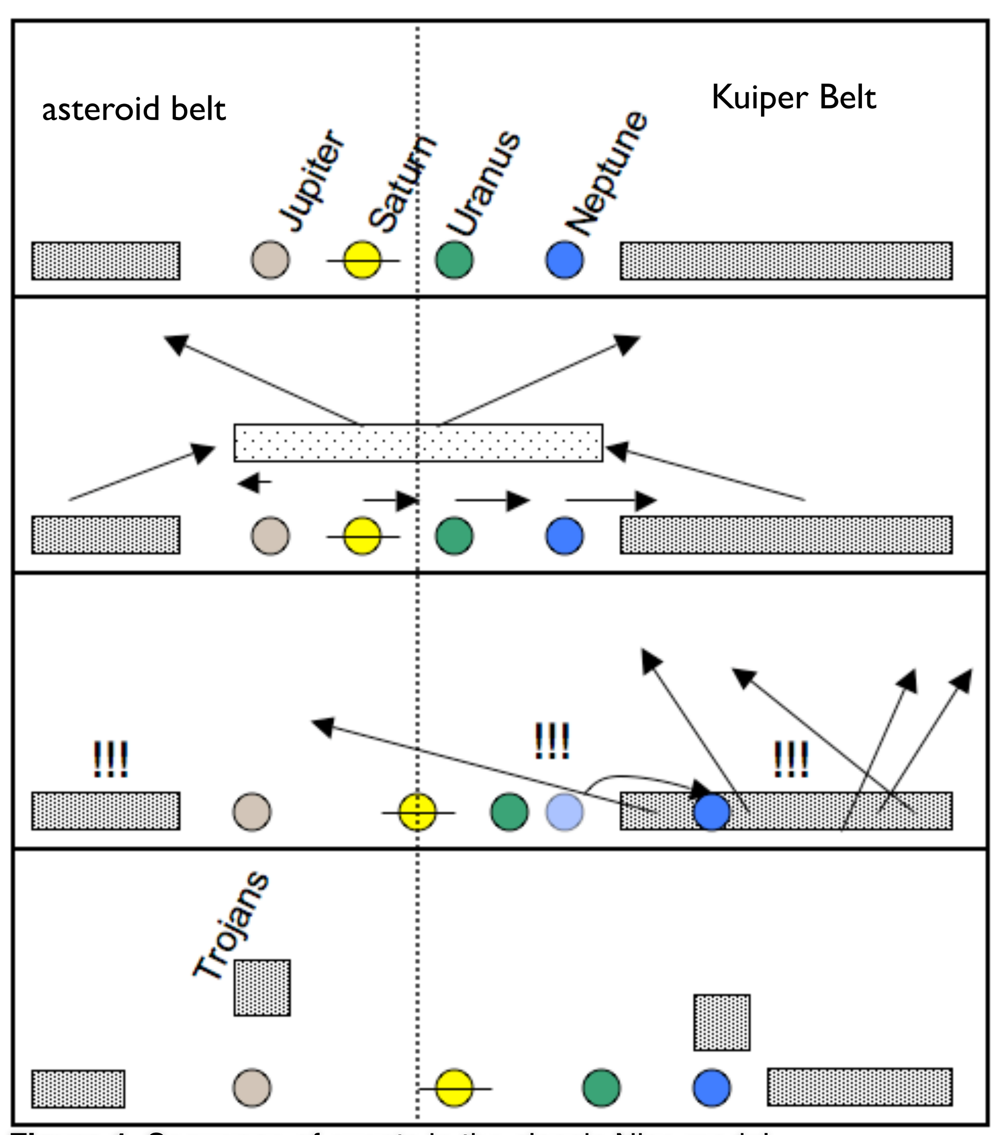

Figure 1. Sequence of events in the classic Nice model

Panel 1: Original locations of the giant planets, along with planetesimal disks [*i.e.*, the ancestral asteroid belt and massive (tens of Earth masses) Kuiper Belt]. At this time the giant planets are closer together than they are now.

Panel 2: Planetesimals slowly leak out of Kuiper Belt and are gravitationally scattered by planets. Backreaction makes Jupiter migrate toward the Sun and makes Saturn, Uranus, and Neptune migrate away from the Sun.

Panel 3: Jupiter and Saturn cross their 2:1 resonance, destabilizing the orbits of the giant planets. Uranus and Neptune migrate into the Kuiper Belt and scatter Kuiper Belt Objects throughout the Solar System. Some collide with planets and satellites. Some asteroids are also scattered out of the main belt due to resonance sweeping.

Panel 4 (today): The planets' retinue consists of a depleted asteroid belt and Kuiper Belt, along with Trojans of Jupiter and Neptune.

Figure courtesy of Andy Rivkin, from Rivkin *et al.* (2010).

Classic Nice results

• **Late Heavy Bombardment of Moon**: $(8.4 \pm 0.3) \times 10^{21}$ g in comets strikes Moon after instability takes place; comparable mass in asteroids hits Moon (Gomes et al. 2005). Mass of impactors needed to make late lunar basins like Imbrium is estimated to be 6×10^{21} g (Levison et al. 2001), so the Nice model produces a Late Heavy Bombardment (LHB) on the Moon (and throughout the Solar System).

• **Ganymede-Callisto dichotomy**: Outer Solar System experiences a much heavier bombardment than the Moon. Ganymede's differentiation (and Callisto's incomplete differentiation) could have resulted from the larger number of impacts it suffers and the higher velocities of the impactors, because Ganymede is closer to Jupiter than Callisto (Barr and Canup 2010).

• **De-Icing**: Impacts during the LHB would have totally stripped some satellites of ice, particularly Mimas, Enceladus, and Miranda (Nimmo and Korycansky 2012).

Did these events really occur?

Figure 2. A noted lab scientist expresses her disdain for numerical modelers.

The heavy comet bombardment in the classic Nice Model is at odds with a number of observations.

• Predicts too many craters and basins on the Moon (Marchi et al. 2012, Bottke et al. 2012)

• Composition of impactor fragments in lunar regolith breccias is consistent with asteroids, not comets (Joy et al. 2012)

• Cometary impacts on main-belt asteroids should have produced many more asteroid families than exist today (Brož al. 2013)

• Icy satellites are still icy (Nimmo and Korycansky 2012)

Let's hope Nice 2 does better!

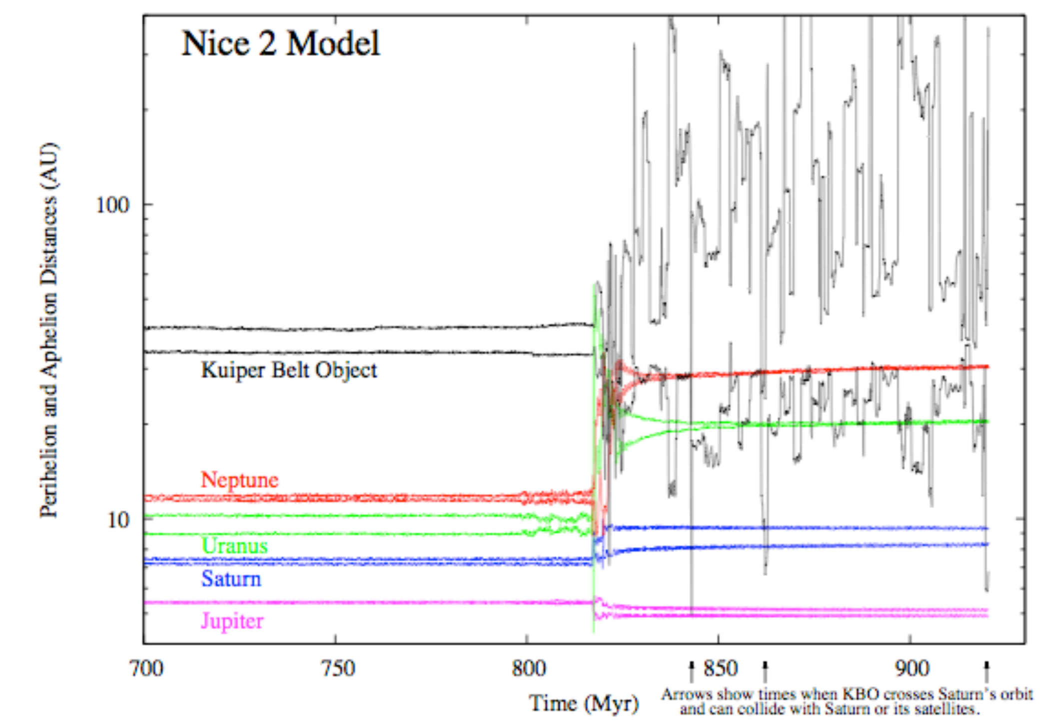

Figure 3. Orbits of the four giant planets and a typical Kuiper Belt Object (KBO) in the "Nice 2" calculations of Levison et al. (2011). The figure begins 700 million years (Myr) after the start of the calculation. The orbits of the planets and KBO are stable until about 820 Myr, and chaotic after that.

Impact rate calculation

Number of impacts on *planets* can be evaluated in two ways:
• **Direct impacts** recorded by SyMBA orbital integrator
• A **statistical code** provided by Bill Bottke (Bottke et al. 1994), based on a program written by Farinella and Davis (1992), that calculates the encounter velocity (v_∞) of a comet with a planet (**Figure 4**) and the probability they will collide.
• **Satellite impact rates** are then calculated using the approach of Dones et al. (2010), which is based on Zahnle et al. (2003). The ratio between the impact rate on a satellite and on its parent planet is insensitive to the encounter velocity for reasonable values of v_∞.

Encounter velocities

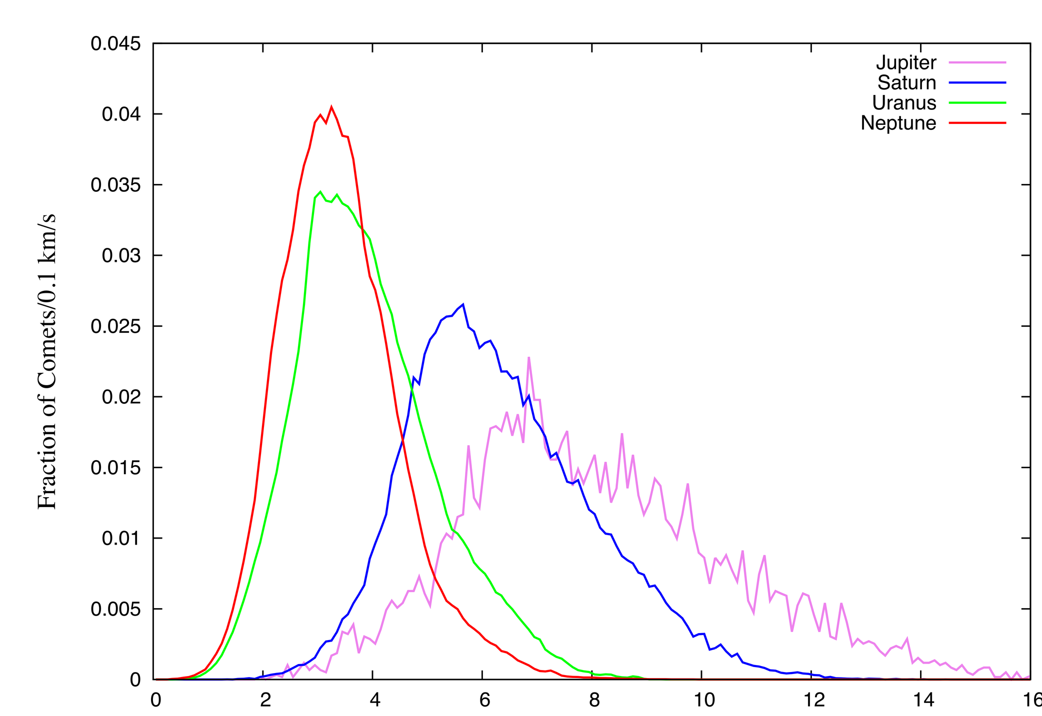

Figure 4. Encounter velocities are higher during the unstable phase of the Nice 2 model than they are in the present-day Solar System. For example, the median impact speed for comets encountering Saturn was 6 km/s, as compared with 3 km/s now.

So what's the answer?

We find that the mass hitting the regular satellites is **smaller** than assumed in studies based on the classic Nice model by a factor of between 3 and 6.

The impact rate is smaller in the Nice 2 model (at least in part) because encounters with the planets cause the orbits of KBOs to become highly eccentric [**Figures 3 and 4**], resulting in less gravitational focusing by the planets. We estimate that assuming *present-day* values of v_∞ (Zahnle et al. 2003) would lead to an overestimate by a factor of about 4 in the impact rate, in agreement with our numerical results.

Furthermore, the latest "hipster" version of the Nice model finds the best match to the population of Jupiter Trojans assuming a planetesimal disk mass a factor of 2 to 4 **smaller** than in the Nice 2 model (Nesvorný and Morbidelli 2013). If we combine this with the factor of 3 to 6 given above, the impact rate on giant planet satellites during the Late Heavy Bombardment appears to be about an order of magnitude smaller than assumed by, e.g., Barr and Canup (2010). In fact, Nimmo and Korycansky (2012) suggested that icy satellites such as Mimas could remain icy if the impact rate was reduced by a factor of ten or so.

The smaller bombardment of giant planet satellites during the LHB is likely to have significant effects, such as formation of impact basins, but not to have resulted in catastrophic disruption or total devolatilization for most mid-sized moons.

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Acknowledgments

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