Unraveling the Early Dynamical Evolution of the Outer Solar System
A Decade of the Nice Model

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One upon a time:

1. The 4 giant planets formed within 15 AU or 20 AU of the Sun.
2. Beyond them was a massive disk that extended to $\sim 30$ AU.
3. The 4 giant planets slowly spread due to leakage from this disk.
4. Jupiter and Saturn crossed the 1:2 mean motion resonance after several 100’s Myr.
   - Uranus and Neptune went unstable and scattered into the disk.
   - Producing the Trojans, Kuiper belt, irregular satellites, primitive main belt asteroids, and lunar late heavy bombardment (LHB).
5. Uranus and Neptune evolve onto current orbits due to interactions with the disk.

And everyone lived happy ever after.
Pruning Parameter Space

- Our original work was intended to represent an example from a large class of evolutionary tracks.
  - We made up or initial conditions, for example.

- There have been several attempts at fine-tuning/pruning parameter space to match other constraints or make the model more physical.
  1. Put the planets in resonances because it is the natural result of planet-disk interactions. \((\text{Morbidelli et al. 2007})\)
  2. Put plutos in disk because they were there. \(\implies\) new trigger \((\text{Levison et al. 2011})\)
  3. Restrict to models where ice giant encounters Jupiter \((\text{Brasser et al. 2009})\)
    - Saves the Earth and asteroid belt.
  4. Added third ice giant. \((\text{Nesvorný & Morbidelli 2012})\)
    - It just works better.
    - Except when it doesn’t.

But the basic story has not changed much.
Crida & Morbidelli (2007)

Morbidelli et al. (2007)
The Effects of Viscous Stirring

- In a non-interacting disk:
  - Planet forces an asymmetry in disk.
  - This is aligned with planet’s orbit \( \implies \) no torque!

- When encounters occur in disk:
  - This asymmetry is no longer aligned.
  - There is a torque on planet!
  - Planet moves.

- Analogous to viscosity in the Earth-Moon system.
  - Without viscosity Earth’s bulge would be below the Moon.
  - With viscosity bulge is offset \( \implies \) Moon moves out.
Can the Nice Model Save the Earth? (Brasser et al. 2009)

- Look what happens when Jupiter migrates smoothly:

- The terrestrial planets become unstable!!!!! 😞
  - Happens because the planets cross *secular resonances*.
  - Happens in Nice model if Jupiter does not encounter an ice giant.
    - Also happens in many other smooth migration scenarios.
  - If the giant planets encounter each other they can jump over resonances.
    - This can save the terrestrial planets.
    - But only works some of the time.

- This is a problem and an active area of research.
Semi-major axes of Jupiter and Saturn during a Nice model simulation. Changes due to encounters with ice giants (Brasser et al. 2009)
Eccentricity of Terrestrial Planets during a Nice model simulation (Brasser et al. 2009)
Note the period of smooth migration before the instability.
The Nice model has done good

- **Giant Planet Orbits:**
  - Smooth migration should leave Jupiter and Saturn on $e = 0$ orbits.
  - Scattering between the planets produce the correct orbits.

- **Trojans:** We get the right number and orbits.

- **Late Heavy Bombardment:**
  - Reproduce duration of magnitude of impacts on Earth and Moon.

- **Primitive and Active Asteroids:**
  - We reproduce the distribution and P and D-types.

- **Asteroid Belt Sculpting:**
  - Realistic smooth migration destroys the asteroid belt.
  - But, encounters between the planets saves it.

- **Irregular Satellites:**
  - Disk particles can get trapped during planetary encounters.

- **Ganymede — Callisto Dichotomy:**
  - Ganymede suffers more impacts than Callisto → differentiated, while Callisto didn’t.
  - Might be an issue for Saturn’s small satellites (Nimmo & Korycansky 2012)
Jupiter Trojans from Morbidelli, Levison, Tsiganis, & Gomes (2005)
From Levison et al. (2009)
From Nesvorny et al. (2006)
From Barr & Canup (2010)
The Kuiper Belt

Rich structure — There are several characteristics that we need to meet:

- There is $\lesssim 0.1 M_\oplus$ of material there. (Trujillo & Brown; Bernstein et al.)
- We need $>10 M_\oplus$ in 30-50AU for them to grow. (Stern & Colwell; Kenyon & Luu; Kenyon & Bromley)
- If it was there, Neptune would have migrated too far.
- The dynamics is a bitch. We need to worry about:
The Nice model can produce a lot of this  
(Levison et al. 2008)

The way it works:

- As Neptune scatters disk particles, they can be temporally trapped in resonances.
- The resonances are wider if Neptune’s eccentricity is large.
- Recall that Neptune goes through a high eccentricity phase as it settles into its current orbit.
- So, the resonances start out wide and decrease with time.
  - Objects can be trapped during this time.
- Can reproduce much of what we see.
  - Given our disk of $45 \ M_\oplus \implies \sim 0.05$ to $0.15 \ M_\oplus$ belt.
    - Observation say between $\sim 0.01$ and $\sim 0.1 \ M_\oplus$.
- It has some problems:
  - We don’t seems to get high enough inclinations
  - The cold classicals.
    - But, they are physically different from the rest of the belt.
- All this predicts that the size-distribution of hot KB and Trojans should be *roughly* the same.
Scattering from Neptune as it is now ($e \sim 0.01$):
Scattering from Neptune with $e = 0.2$:  

![Graph showing semi-major axis vs. eccentricity with Kuiper belt indicated.]}
From Tsiganis et al. (2005)
Cold Classicals

- These objects are physically different.
  - Different colors (cf. Sheppard 2010)
  - Different binary fraction (cf. Null. et al.)
- There are claims that they are primordial.
  - because they don’t fill stability zone.
  - This is untrue.
- Levison et al. (2008) can’t make them.
  - It will destroy the binaries.
- Primordial?
  - Must still explain where the mass went.
- Implanted?
  - Levison & Morbidelli (2003) might need to be resurrected.
  - Might need a period of smooth migration followed by instability.
- I’m confused.
- In any case, they are a unique population to visit!
From Noll et al. (2008):
From Morbidelli et al. (2013):
Levison & Morbidelli (2003):
A 5 planet case from Nesvorný & Morbidelli (2012):

Note the period of smooth migration before the instability.
A 5 planet case from Nesvorný & Morbidelli (2012):
The disk beyond the Kuiper belt.

KBO distribution shows the gas disk was truncated. \( \text{(Krette et al. 2012)} \)

- As Jupiter and Saturn form they scatter objects outward.
- If the gas disk went to large distance, Kozai becomes important.
  - It exchanges \( i \) for \( e \) \( \rightarrow \) objects evolve onto large \( q \) large \( i \) orbits.

- As the gas disk disperse, objects will be trapped in ultra-high \( i \) KB orbits.
- The DES survey would have seen them if the disk was there.

\( \rightarrow \) When the gas giant formed the gas disk was truncated at \( \lesssim 60 \) AU.
Size-distribution based on Fraser et al. (2010)'s ‘hot’ population.

\[ \sum(r, t) \propto r^{-\gamma} \Theta(r, R_D) e^{-t/\tau_D} \]

Left:

- \( \Theta = \Theta_{\text{cut}} \equiv 1 \) if \( r < R_D \) and 0 elsewhere.
- Blue \( \rightarrow \gamma = 1 \), Black \( \rightarrow \gamma = 3/2 \),

Right:

- \( \Theta = \Theta_{\text{exp}} \equiv e^{-r/R_D} \)
- Blue \( \rightarrow \gamma = 1/2 \), Black \( \rightarrow \gamma = 1 \),
Conclusions

▶ The Nice model is alive and well after almost a decade.
▶ It faces some issues:
  1. Are ‘predictions’ about the size-distribution of objects is right?
  2. The cold classicals.
     ▶ If they are primordial, where did the mass go?
     ▶ If they are embedded, how did they get there?
     ▶ We need to go and look at one!
▶ What we really lack is a competitor that is developed as far.
▶ The Kuiper belt is the best place to test these ideas.

This talk can be found at www.boulder.swri.edu/~hal/talks.html.
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