The `Nice’ Model

Planet migration in a planetesimal disk
The Nice model
Consequences of the Nice Model: Epoch of Late Heavy Bombardment, Kuiper belt and asteroid belt distribution, Trojan asteroid distribution
Planet migration in planetesimal disks

- Objects with semi-major axis exterior to planet $a > a_p$ cross the planet’s orbit with velocities higher than the planet. Relative velocity is in direction of rotation.
- Hyperbolic orbit velocity change. Planet is sped up and so moves outwards. Neptune migrating outwards.
- True unless particles are eventually ejected, in this case the planet must lose energy and move inwards. Most massive planet tends to migrate inwards.
- Fernandez & Ip 94
- Later applied toward capture of Pluto by Renu Malhotra
- Planet migration may be needed to explain hot Jupiters, though tightly packed Kepler systems suggest that planet formation can take place at small radii
Planet migration in planetesimal disks
following Ida et al. 00, Gomes et al. 03 and recent reviews by Levison & Morbidelli

- Planet migration rate depends
  on rate that angular momentum
  is passed between planet
  and planetesimals, $H_x$
- $\varepsilon$ fundamental constants
- $k$ fractional angular momentum change
- $M(t)$ is mass in planetesimals that are in planet
  crossing orbits
- Approximate $\dot{M}(t) \sim -M(t)/\tau + 2\pi a_p \dot{a}_p \Sigma(a_p)$
- $\tau$ dynamical lifetime of orbit crossing bodies
- $\Sigma$ planetesimal density outside of planet’s orbit
Planet migration

- Solutions are either exponentially growing or damping
- “damped migration” Migration rate drops to zero exponentially if disk density is below a critical value (Gomes et al. 03)
- Otherwise: “sustained”
Initial conditions: 4 giant planets were initially much closer together. The planetesimal disk was located just outside Uranus and extended from 15-34 AU and was about $35 M_{\text{earth}}$.
Nice Model

- Planets slowly separating due to scattering of planetesimals
- Saturn and Jupiter enter a 2:1 mean motion resonance
- Because Jupiter and Saturn are moving apart this is not a resonance capture
- Jupiter and Saturn increase in eccentricity during resonance crossing
- Other bodies in solar system violently affected. Secular perturbations after Jupiter and Saturn increase in eccentricity cause orbit crossing of outer planets
- Neptune and Uranus separate from Saturn and Jupiter and perhaps switch position (~50% of simulations)
- Entire outer planetesimal belt is scattered leaving only a remnant behind

3 papers appearing in Nature in 2005 + a fourth later revised in 2011, then extended with Grand Tack
Nice Model

- Giant planets left with non-zero eccentricities
- Scattering and migration damps planet eccentricities, and so previous models for evolution of outer solar system have had difficulty accounting for their values
- Regular satellites can survive during the epoch of large eccentricities. Irregular satellites can be lost or captured
- Some sensitivity of model to dispersion, mass and extent of initial disk and initial positions of giant planets
Trojan population

Rapidly changing stability in corotation region during resonances allows capture with a large range of inclinations and eccentricities.

Figure Comparison of the orbital distribution of Trojans between model (filled circles) and observations (dots). The distribution of the simulated Trojans is somewhat skewed towards large libration amplitudes, relative to the observed population. However, a fraction of the planetesimals with the largest amplitudes would leave the Trojan region during the subsequent 4 Gyr of evolution, leading to a better match.
Late Heavy Bombardment

The planetary orbits and the positions of the disk particles. The four giant planets were initially on nearly circular, co-planar orbits with semi-major axes of 5.45, 8.18, 11.5 and 14.2 AU. The dynamically cold planetesimal disk was 35M, with an inner edge at 15.5 AU and an outer edge at 34 AU.

Four different epochs are shown: a, the beginning of planetary migration (100 Myr); b, just before the beginning of LHB (879 Myr); c, just after the LHB has started (882 Myr); and d, 200 Myr later, when only 3% of the initial mass of the disk is left and the planets have achieved their final orbits.

Gomes et al. 05, Nature
Late Heavy Bombardment

The cumulative mass of comets (solid curve) and asteroids (dashed curve) accreted by the Moon. We have offset the comet curve so that the value is zero at the time of 1:2 MMR crossing. Thus, $5 \times 10^{21}$ g of comets was accreted before resonant crossing and $9 \times 10^{21}$ g of cometary material would have struck the Moon during the LHB. Gomes et al. 05
Late Heavy Bombardment

- A delay between planet formation and bombardment that is set by slow migration timescales
- Mix of asteroid and cometary material for bombardment
- Association of Late Heavy Bombardment with dispersal of planetesimal disk
Additional consequences

- Migration of Jupiter swept resonances through asteroid belt (Minton & Malhotra, 2009, Nature). Provides a better match to asteroid belt distribution
- Irregular satellite population seems to remain a difficulty to explain (Vokrouhlický et al. 08) though some can be captured (Nezvorny et al. 07)
- Stability of Terrestrial planet region (need citation!!!!)
Structure of Kuiper Belt

- High Inclination distribution has always been a problem for resonant capture models to explain Plutinos

Observed KBO objects
Levison, H. F. et al. 08, Icarus, 196, 258
**Nice model and the Kuiper Belt**

- Eccentricity variations of Neptune during 2:1 Saturn/Jupiter resonant crossing event led to scattering of the outer planetesimal disk
- Natural depletion of disk
- Many objects scattered by Neptune and Uranus → high inclination objects
- Objects scattered early have higher inclinations → possible relation between mass, composition and orbital properties
- Resonant and non-resonant populations are a natural consequence - Dynamics possibly a combination of chaotic capture, and islands of stability and migration into a hot disk type of model
- Slight shortage of low eccentricity low inclination objects in model
- Good match to disk edge

Simulation resembles Kuiper belt much more so than other models? but objects like Sedna not predicted
Nice model

• Planetary and planetesimal architecture better explained by this single scenario than any other
• Stats of debris disks now being interpreted in terms of this model
• It is possible that all planetary systems contain multiple packed planets, large reservoirs of planetesimals and so go through periods of violent instability
• Stability affected by mass of planetesimal reservoir and ordering of planet masses (Thommes et al. 08)
Case studies

• HR8799A system - 4 massive planets near a debris disk. Likely will undergo a shake-up. Either dropping out of stabilizing resonance due to migration or encountering another resonance due to migration.
• Formalhaut system. 1 known planet, likely eccentric near an eccentric but old disk. Coldness of disk rules out as violent a shake-up as Nice model, or shakeup happened when disk still had gas in it so that the disk damped to a cold eccentric shape.

--> Instabilities are common. All debris disks detected after instabilities in planetary systems?
HST image of HR4796A shows an inner hole in the disk suggesting that there are planets in the system.

G. Schneider + collaborators
HR8799 system

- HR 8799, A star, young!
- Hosts a debris disk
- 4 massive planets
- Discovered via optical imaging

Marois et al. 2011

<table>
<thead>
<tr>
<th>Companion</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period (years)</th>
<th>Radius</th>
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<td>e</td>
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<td>14.5 ± 0.5</td>
<td>~45</td>
<td>? (R_J)</td>
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<td>d</td>
<td>(7^{+3}_{-2} M_J)</td>
<td>24±0</td>
<td>~100</td>
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<td>68±0</td>
<td>~460</td>
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<td>Dust disk</td>
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<td>6 – 1000 AU</td>
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evidence of debris
Fomalhaut

Recent ALMA submm data with HST scattered light
Beta Pictorus

Hubble Space Telescope • ACS/HRC

Location of Star

Primary Disk

Secondary Disk

Occulting Mask

10 billion miles
100 AU

NASA, ESA, and D. Golimowski (Johns Hopkins University)

STScI-PRC06-25
8 Jupiter mass planet at 8 AU
Case studies
Planets + Disks

Kepler 36 system
embryos needed to explain proximity and high density contrast

Resonant stack up of KOI 730 system.
Very little debris can pull the system out of resonance

HR 8799, debris does not stabilize rather the system will soon fall apart
Mars Problem

- models of terrestrial planet formation tend to predict bodies more massive than Mars forming in the asteroid belt (Raymond et al. 2009)
Grand Tack Model

• Possible solution to the Mars problem
• Early (first Myr), Jupiter moves inwards truncating the outer asteroid belt.
• Then Jupiter migrates outwards (Walsh, Kevin et al. 2011, Nature)
Disk of rocky planetesimals → Jupiter → Saturn → Disk of water- and carbon-rich planetesimals

Truncated disk (0.7-1.0 au) → Scattered planetesimals

Jupiter and Saturn move inward until Saturn reaches final mass

Terrestrial planets form from this

S-type asteroids

C-type asteroids

Jupiter and Saturn move outward

Orbital distance from Sun
Reading

• 3 Nature papers proposing and exploring the Nice model
  – also see: Levison, H. F. et al. 2008, Icarus, 196, 258, Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune
  – Update on the grand tack
    – http://www.boulder.swri.edu/~kwalsh/GrandTack.html