Planet migration in the Solar system

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The solar system has not always looked like it does now (@ age of 4.567 Gy)

@ 4.5 Gyr ago: orbits more compact + a lot more debris (asteroids, comets)
@ 3.9 Gyr ago: debris cleared up (mostly), planets settled into their present orbits
A little bit about me …

I am interested in the “architecture” of planetary systems
- how planetary masses and orbits are arranged
- how they form and change over time

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Tucson
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physics + astronomy + mathematics
my own peregrinations…
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New Delhi 1961-1968

Hyderabad 1968-1978

New Delhi 1978-1983
St. Ann’s School, Secunderabad, India

Indian Institute of Technology, Delhi

all-girls school

~3%
St. Ann’s School, Secunderabad, India

all-girls school

~3%
Undergraduate: Physics

Graduate studies: Physics

Dynamical systems - chaos theory

Planetary dynamics/planetary science
factors that have been important in my life and career

- curiosity
- ignoring distractions
- perseverance
- perfectionism

- broad-minded parents
- teachers & mentors
- partner
- USA ... country & society

- adversity
- & serendipity
On to planets...
Ancient concept of cosmos

eternal, unchanging

planets

Moon

Sun

Earth
Modern concept of the cosmos

Earth is a planet in the solar system … in the Milky Way Galaxy … in the Local Cluster of galaxies … in the Universe
Modern concept of the cosmos

Earth is a planet in the solar system …
in the Milky Way Galaxy … in the Local Cluster of galaxies … in the Universe

*evolves on many timescales*
Four or Five distinct neighborhoods in the Solar system
also some stragglers in-between (NEOs, Centaurs)
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circa ~1990 … Nine planets in the solar system
Pluto is eccentric
its orbital path overlaps that of Neptune
but it is in no danger of colliding with Neptune
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20,000 year libration
Neptune’s migration and Resonance sweeping
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Prediction: pile-ups of KBOs in resonances
Giant planet migration fueled by leftover planetesimals

Solar system @ ~4 Ga

Solar system ~today

Ejected

Scattered

Oort Cloud

Cleared

Surviving debris
Planetesimal clearing → back-reaction on the planets
Planetesimal clearing $\Rightarrow$ back-reaction on the planets
Planetary clearing → back-reaction on the planets

Jupiter...Neptune + trillions of planetesimals → Jupiter migrates inward, Neptune migrates outward
The origin of Pluto’s peculiar orbit

Renu Malhotra

\[ e_{P,\text{final}}^2 - e_{P,\text{initial}}^2 \approx \frac{1}{j+1} \ln \left( \frac{a_{N,\text{final}}}{a_{N,\text{initial}}} \right) \]

Pluto’s resonance and eccentricity

Neptune’s migration

\[ e_P = 0.25 \Rightarrow \Delta a_N \approx 5 \text{ au} \]

Confirmed with computer simulations
Kuiper Belt observations
Kuiper Belt observations

resonances, eccentricities, inclinations

\[\Rightarrow \text{Neptune migrated out} \gtrsim 10\text{AU}\]
Other observational tests?

Asteroid belt

Impact craters on planetary surfaces
Asteroid belt - Kirkwood gaps

Asteroid Main-Belt Distribution
Kirkwood Gaps

image: wikipedia
Asteroid belt - Kirkwood gaps

Kirkwood related the locations of the gaps to mean motion resonances with Jupiter.

Discovered by Daniel Kirkwood in 1857, when less than 100 asteroids were known.
Asteroid belt - Kirkwood gaps

Kirkwood related the locations of the gaps to mean motion resonances with Jupiter.

The gaps sizes are best explained if Jupiter migrated inward from a slightly larger orbit.

Discovered by Daniel Kirkwood in 1857, when less than 100 asteroids were known.

Clues in the impact crater record

- Two different populations of craters

Mercury

Moon

Venus

Mars
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- Two different populations of craters

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Summary

• The solar system has not always looked like it does now (@ age of 4.567 Gy)
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  @ ~4 Gyr ago: debris cleared up (mostly), planets settled into their present orbits

• That early dynamic period had major consequences
  ✦ planetary re-arrangements ⇒ (more) stable orbits
  ✦ heavy meteoroidal bombardment
  ✦ very little asteroidal/cometary debris left, hence low bombardment rate on Earth

• Details under active study and debate