Origin and Dynamical structure of the Trans-Neptunian Belt: Evidence for an Outer Planet in the Solar System

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Planet and planetesimal formation

Protonoptune

>4Gyr

Distance from the Sun

(Montmerle et al. 2006)

Planet migration

Planet and planetesimal formation

>4Gyr
Trans-Neptunian objects (TNOs) are icy bodies orbiting beyond Neptune...

Four main classes of TNOs:
- Resonant
- Classical
- Scattered
- Detached

(e.g., Lykawka & Mukai, 2007b)

Outstanding questions
→ What caused the primordial excitation of the Kuiper belt? (excitation of $e$ and $i$ around 40-50AU)
→ How to explain the four main classes of TNOs?
→ What is the nature of the Kuiper belt outer edge at about 48AU?
A large planetesimal (the outer planet) with tenths of $M_\oplus$ is scattered by a giant planet. The planetoid excites the planetesimal disk for several tens of Myr, before planet migration.

The planetoid is captured by a strong Neptunian resonance of the type $r:1$, which then transports it to $\gtrsim100$AU.

The Kozai resonance (KR) forces the planet’s eccentricity to decrease at the expense of increasing its inclination.

1. **Formation stage**: A large planetesimal (the outer planet) with tenths of $M_\oplus$ is scattered by a giant planet.

2. **Pre-migration stage**: The planetoid excites the planetesimal disk for several tens of Myr, before planet migration.

3. **Migration stage**: The planetoid is captured by a strong Neptunian resonance of the type $r:1$, which then transports it to $\gtrsim100$AU.

4. **Long-term sculpting stage**: The Kozai resonance (KR) forces the planet’s eccentricity to decrease at the expense of increasing its inclination.
General Results

$\alpha_P = 100\text{AU}$

$q_P = 80\text{AU}$

$i_P = 35^\circ$

$M_p = 0.4M_\odot$

2 Pre-migration stage

3 Migration stage

4 Long-term sculpting

Observations

Semimajor axis (AU)
General Results

2. Pre-migration stage

3. Migration stage

4. Long-term sculpting

Observations

Eccentricity vs. Semimajor axis (AU)
Resonant Populations

Planetesimal disk initially extended to \( a \approx 5\text{AU} \)

Production of resonant TNOs with orbital and resonant properties compatible with observations
Observations Simulation

Planetesimal disk initially extended to $a \sim 51$ AU

Production of scattered and detached TNOs

- $(30 \text{AU} < q < 40 \text{AU}; 0 < i < 50^\circ)$
- $(40 \text{AU} < q < 60 \text{AU}; 0 < i < 60^\circ)$

(including analogs of Eris, 2004 XR$_{190}$, 2000 CR$_{105}$ and Sedna)
Planetesimal disk initially extended to $a \sim 51$AU

Production of classical TNOs with orbital excitation in excellent agreement with observations
The Belt’s Outer Edge

Planetesimal disk initially extended to $a \sim 51$ AU

Effective production of an outer edge at $a \sim 48$ AU: absence of low-$e$ objects AND abrupt number density decrease
Observational Constraints for the Trans-Plutonian planet

Best orbital elements for the planetoid: $a_p = 100$-$175$ AU, $q_P \geq 80$ AU, $i_P = 20$-$40^\circ$
Summary

Our model with a trans-Plutonian planet can explain \textbf{consistently} the:
1) excitation of the Kuiper belt
2) the belt’s outer edge at $\sim$48AU
3) origin of the four main populations of TNOs
4) loss of $\sim$99% of the Kuiper belt initial mass
5) Neptune’s current orbit at 30.1AU

Conclusions

- A massive body (outer planet) was scattered by one of the giant planets during late stages of planet formation
- It then stirred the primordial planetesimal disk to the levels observed at 40-50AU and truncated it at $\sim$48AU, before planet migration (fossilized signatures)
- Later, the outer planet acquired an inclined stable orbit because of a resonant interaction with Neptune
- \textbf{Long-term signatures} of the planetoid’s perturbation are the detached and very high-$i$ populations ($>40$ degrees)
Ongoing/Future Work

1. Systematic exploration of compact systems of giant planets + embedded planetoids in massive disks
2. Influence of more massive outer planets ($\geq 1M_\oplus$) with lifetimes $<1$Gyr to produce more “Sednas” and explain the Late Heavy Bombardment
3. Origin and long-term dynamical evolution of Neptune Trojans and collisional families in the Kuiper belt
4. Implementation of collisional fragmentation in MERCURY (a N-body code)
5. Implementation of effects of stochasticity in planet migration
6. Detailed analysis of the dynamics of Centaurs, scattered disk objects and other unstable TNOs
FIM
有難うございました

惑星X
カイパーベルト
海王星
小惑星帯
地球

エリス
冥王星
地球