THE TRANS-NEPTUNIAN REGION ARCHITECTURE:

A FORMATION SCENARIO

KOBE UNIVERSITY

Graduate School of Science and Technology - Earth & Planetary System Sciences, Japan

Patryk Sofia Lykawka and Tadashi Mukai

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PART I

INTRODUCTION
The main populations are: classical, resonant, scattered, and detached TNOs* (Morbidelli & Brown 2005)

* TNOs with semimajor axis $a>48$AU and perihelion $q>40$AU represent a new class: detached TNOs (Delsanti & Jewitt 2006)

Evolutionary processes: planetary migration, collisional evolution and long-term gravitational sculpting by the planets (Malhotra 1995; Hahn & Malhotra 1999; Kenyon & Luu 1998, 1999; Kenyon & Bromley 2004; Morbidelli 2006; Chiang et al. 2006)

= Neptune
= Pluto
= 2003 UB₃₁₃
Outstanding questions:

→ Which TNOs are in resonance with Neptune?
→ What is the real ratio of 2:1 to 3:2 resonant TNOs?
→ What caused the lack of low eccentricity TNOs beyond ~45AU?
→ What is the origin of detached TNOs in the scattered disk?
→ Are scattered TNOs in resonance?
→ Could the origin of detached TNOs be resonances?

(Gomes et al. 2005, Lykawka & Mukai 2006a)
Zoom in: the scattered TNOs (>48AU).

(Torbett 1989; Holman & Wisdom 1993; Duncan & Levison 1997; Morbidelli et al. 2004)

(Eccentricity vs. Semimajor axis)

(Dez/2005)
PART II

Long-term evolution of classical TNOs

Earth, Moon, and Planets – online (2006b)
Simulations

Uniform distributions

13485 particles
4474 particles

4Gyr
Strong perturbation for $q<37-38\text{AU}$, $41.5-42\text{AU}$ and near the 5:3 and 2:1 resonances. However, no evidence for instability in the outer part ($>45\text{AU}$).
PART III

Dynamical classification and resonance occupancy in the trans-Neptunian region

Submitted to Icarus (2006d)
**Simulations**

**Kuiper belt** \((a < 48\text{AU})\)
- 468 TNOs + 10 clones of each body
- total = 5148 particles

**Scattered disk** \((a > 48\text{AU})\)
- 67 TNOs + 100 clones of each body
- total = 6767 particles

Orbital elements taken from the Lowell Observatory database (only long-arc objects)

Lykawka, P. S. & Mukai, T. TNO Workshop, Catania, 3-7 July 2006
Proper elements and accurate dynamical boundaries determined, resonant TNOs identified and new detached TNOs found.

The four classes:

- Resonant TNOs
- Classical TNOs ($q>37-38$ AU; $37$ AU < $a$ < $48$ AU)
- Scattered TNOs ($q<37$ AU)
- Detached TNOs ($q>39.5-40$ AU)
Detached TNOs

- (48639) 1995 TL$_8$ (40.0AU)
- 1999 HW$_{11}$ (39.4AU)
- 2000 CR$_{105}$ (44.2AU)
- (82075) 2000 YW$_{134}$ (40.7AU)
- 2003 QK$_{91}$ (38.5AU)
- 2003 UY$_{291}$ (41.2AU)
- (90377) Sedna (76.3AU)
- 2004 OJ$_{14}$ (39.9AU)
- 2004 XR$_{190}$ (51.4AU)

Apparent fraction beyond 48AU: \(~15\%\)
(9 out of 67 bodies)
MORE RESULTS

- Objects of interest *not* in resonance

**Kuiper belt:**
- Varuna, Quaoar, 2003 EL$_{61}$ (?), 2005 FY$_{9}$

**Scattered disk:**
- All detached TNOs $(q > 39.5-40$AU) except 2000 YW$_{134}$ (8:3).
  *Thus, in principle resonances cannot explain their origin*
- 2003 UB$_{313}$
Summary: 166 resonant TNOs

(*) = number of Kozai resonants

Kozai resonance: a secular resonance that causes large variations of eccentricity and inclination (anticorrelated) \( \rightarrow \) conservation of \( \sqrt{1-e^2 \cos i} \)
What is the origin of long-term resident resonant TNOs?
PART IV

Origin of resonant TNOs in the Scattered disk: evidence for an excited Kuiper Belt of 50AU radius

Submitted to Icarus (2006c)
Scattered disk (SIM1)
- 26500 particles
- 4Gyr

Excited Kuiper belt + scattered disk (SIM2)
- 91600 particles*
- 100Myr + (migration)
- 4Gyr
Amplitude of the resonant angle for objects in resonance

(Amplitude of the resonant angle = approximate criterion for stability inside a resonance)

Filled circles: observed scattered disk TNOs
Open circles: particles captured from the scattered disk (SIM1, SIM2)
Boxes: range of values for particles captured by sweeping resonances (SIM2)
Initial orbital elements of particles captured in the 5:2 resonance during Neptune’s migration (crosses)

We emphasize only the particles with final $e=0.35-0.44$ (constrained by 5:2 resonant TNOs) and that survived 4Gyr (black circles).
Initial orbital elements of a planetesimal disk needed for the capture of currently observed 9:4, 5:2 and 8:3 resonant TNOs.

Primordial planetesimal disk extended to 45-50AU or more!
To create the resonant populations in the scattered disk, a mechanism **MUST** have excited the ancient Kuiper belt!

**But what...?**
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=100\text{Myr}$ * Just after Neptune (at 20AU) & TNOs formation
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

* Dynamical mechanism perturbing the edge of the belt
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$\textit{t=125}\text{Myr}$  * Dynamical mechanism perturbing the edge of the belt*
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=140\text{Myr}$ * Dynamical mechanism perturbing the edge of the belt*
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=150\text{Myr}$

* Planetary migration starts!

$t_{\text{mig}}=0\text{Myr}$
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=152\text{Myr}$  
* During planetary migration  
$t_{\text{mig}}=2\text{Myr}$
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

\[ t = 155 \text{ Myr} \quad \text{* During planetary migration} \quad t_{\text{mig}} = 5 \text{ Myr} \]
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

\[ t = 160 \text{ Myr} \quad \text{* During planetary migration} \quad t_{\text{mig}} = 10 \text{ Myr} \]
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=165\text{Myr}$ * During planetary migration $t_{\text{mig}}=15\text{Myr}$
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

Lykawka, P. S. & Mukai, T. TNO Workshop, Catania, 3-7 July 2006

$t=175\,\text{Myr}$ * During planetary migration \hspace{1cm} t_{\text{mig}}=25\,\text{Myr}
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=200-230\,\text{Myr} \quad \text{* Planetary migration ends} \quad t_{\text{mig}}=50-80\,\text{Myr}$
Time evolution for the dynamical excitation of the primordial Kuiper belt (sketch)

$t=0.23-4.5\text{Gyr}$ * Formation of the scattered disk and long term dynamical evolution
Observations support this early dynamical perturbation

The ancient Kuiper belt extended to at least 45-50AU and was dynamically perturbed to $e=0.1-0.3$ or even more
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PART V

SUMMARY AND FUTURE WORK
SUMMARY

LONG-TERM EVOLUTION OF CLASSICAL TNOs

• Objects are mostly stable at 42AU and beyond, provided q>37AU or trapping in a local resonance. This stability is in contrast with the lack of TNOs in the outer Kuiper belt (>45AU)

DYNAMICAL CLASSIFICATION AND RESONANCE OCCUPANCY IN THE TRANS-NEPTUNIAN REGION

• All TNOs are dynamically found in four distinct classes: resonant, classical (q>37-38AU; 37AU<a<48AU), scattered (q<37AU) and detached TNOs (q>39.5~40AU)
• Resonances alone cannot explain the origin of detached TNOs
• Stable resonant TNOs currently inhabit both the Kuiper belt and the scattered disk

ORIGIN OF RESONANT TNOs IN THE SCATTERED DISK: EVIDENCE FOR AN EXCITED KUIPER BELT OF 50AU RADIUS

• Long-term resonant TNOs in the scattered disk (4~4.5Gyr) must have originated from sweeping resonances over a previously excited Kuiper belt. This requires a primordial planetesimal disk extending to 45-50AU and an excitation mechanism operating during the early solar system
THE END

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