Exploring evolutionary paths and resonance sticking of scattered TNOs

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Introduction

According to solar system formation studies, it is believed that scattered transneptunian objects (TNOs) were scattered by the giant planets to highly excited and large orbits in the transneptunian region (Morbidelli et al., 2003). In general, these objects show large eccentricities and moderate to high inclinations, and constitute the transneptunian scattered region (figure 1). With no strict neither official definition, we set the TNOs with a>48AU and q>30AU as scattered TNOs. Furthermore, the so-called extended scattered TNOs possess perihelion distances large enough (q>40AU) to be considered a distinct class. They are not supposed to arise from the standard theory of scattering by a protoneptune (Gladman et al., 2002), so that their origin must imply another dynamical process.

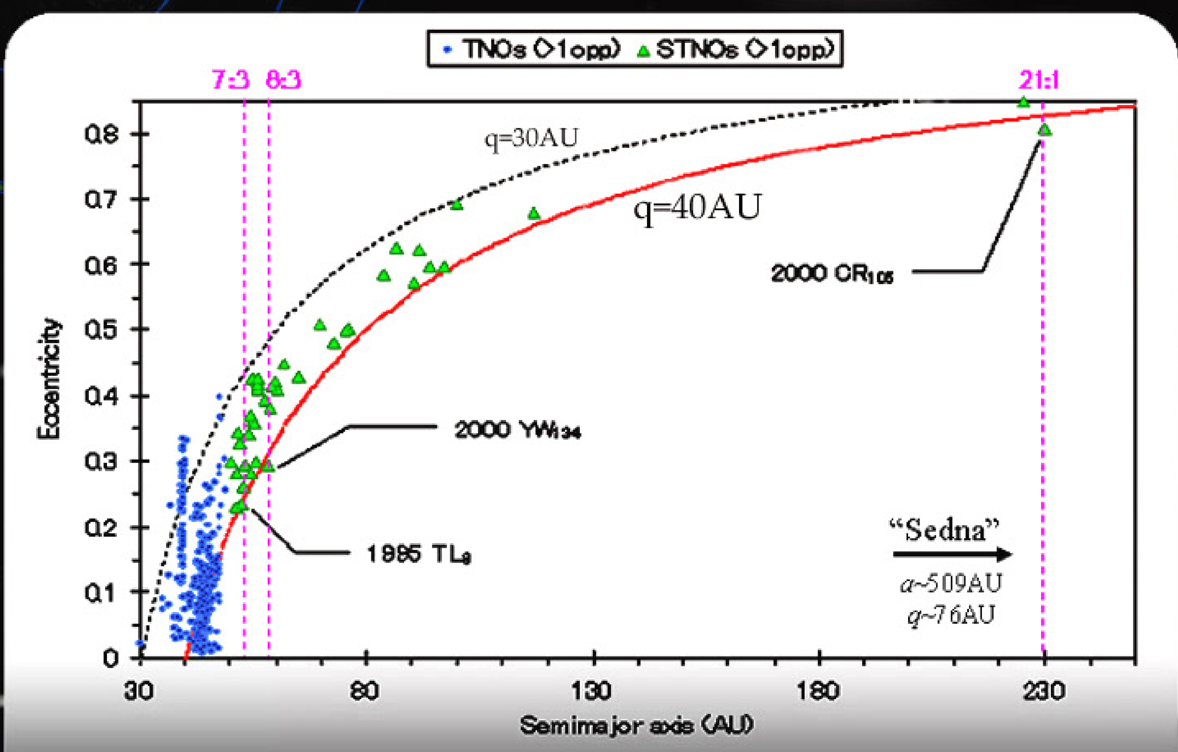

FIGURE 1: Orbital data of TNOs and scattered TNOs (STNOs) with more than one opposition observations (data taken from the Minor Planet Center).

→ What is the origin of scattered objects with large perihelion (q>40AU)?

Namely: 1995 TL_8 (q=40.1AU), 2000 YW_{134} (q=41.2AU), 2000 CR_{105} (q=44.3AU) and 2003 VB_{12} "Sedna" (q=76.1AU)

Proximity to resonant places is suggestive for their origin.

→ How do objects evolve in the scattered region?

Method

We performed 7 simulations to investigate the origin, formation and evolution of scattered TNOs. Integrations were conducted for 4-5Gyr including fully the four giant planets gravitational influence and more than 45000 massless particles. The initial conditions covered specific source regions: 40-42AU unstable region, classical region, resonance places and scattered region. The EVORB package (Brunini & Melita, 2002) was used for all major 4-5Gyr integrations.

Main Results

Evolutionary paths

About 1-2% of the bodies survived in the scattered region following typical chaotic orbits (figure 2).

We found that all scattered particles experienced single or multiple temporary capture into different resonances, a phenomenon known as resonance sticking (Duncan & Levison, 1997).

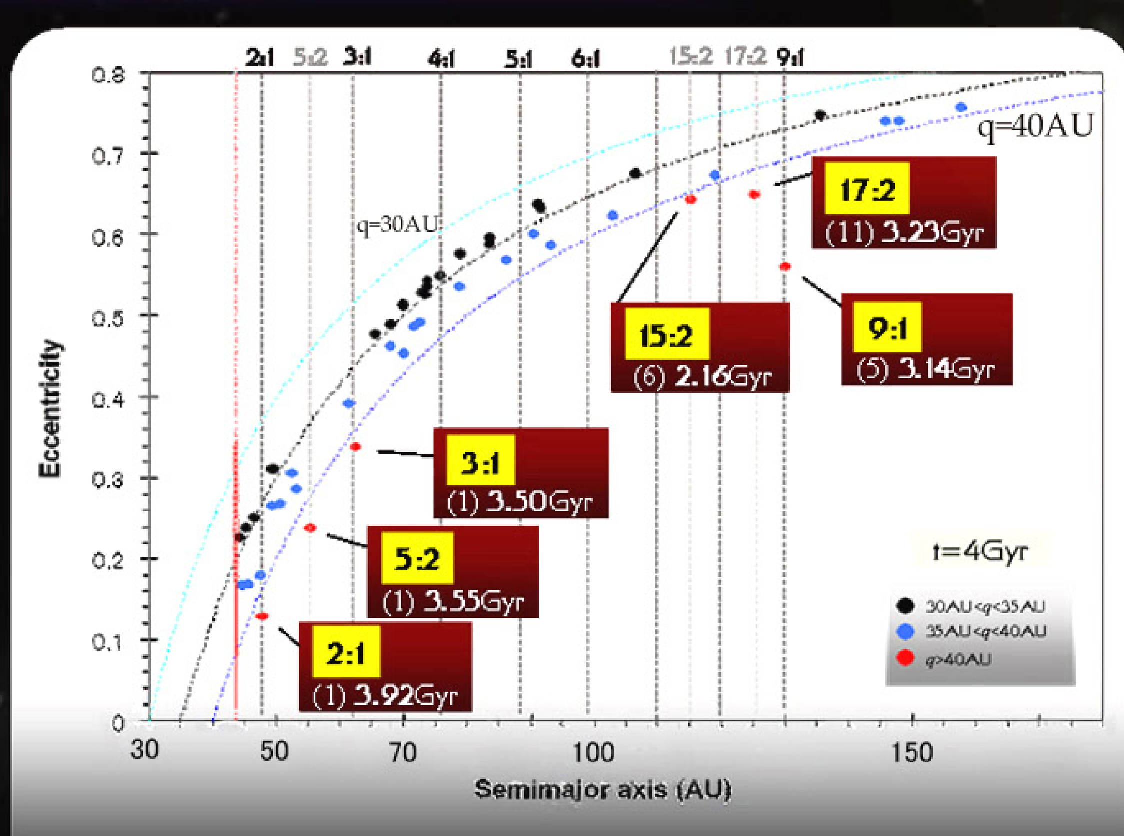

FIGURE 2: Scattered bodies after 4Gyr for one of the simulations. At least six objects have large perihelia (q>40AU) associated with resonances. The number of different trapped resonances (in parentheses) and the total trapped time is also shown.

Resonance sticking and stability

- Resonances provided protection against close encounters with Neptune (libration mechanism)
- Perihelion increased proportionally to the resonances residence time

Both features imply that resonance sticking is the main mechanism helping to enhance dynamical longevity in the scattered region.

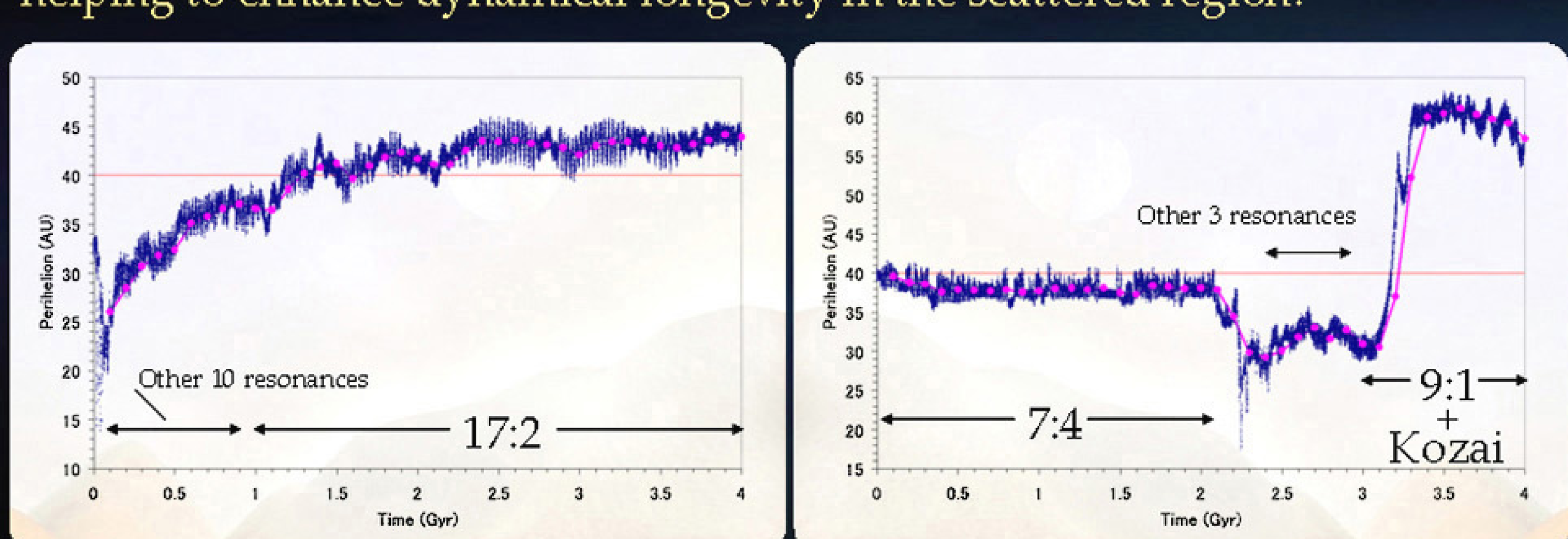

FIGURE 3: Two typical examples of resonance sticking and the increase of perihelion associated with specific resonances as showed on the plots (see also figure 4).

Resonance sticking: typical behaviour

All scattered particles experienced alternation between scattering and temporary resonance sticking in the scattered region. Time scales for residence time inside resonances varied from million to billion of years. A typical case is shown in figure 4. Although the evolution was chaotic in nature, resonance sticking seems to work following preferential paths in phase space. That is, a body temporarily trapped in a $p{:}q$ resonance is likely to migrate to another $r{:}s$ resonance obeying a relation between the $p{:}q$ resonance and a $t{:}1$ resonance. We would have $(r{:}s)=(p+t){:}(q+1)$ or $(p-t){:}(q-1)$. We call this the sticking relation[1]. (e.g., for 4:1, 5:1 and 7:1 governing resonances, a possible path could be 9:2→14:3→21:4→17:3.). Another example can be seen from the figure.

[1] Most of the evolutionary paths were well described by this relation. Some particles migrated to $t{:}1$ resonances as well.

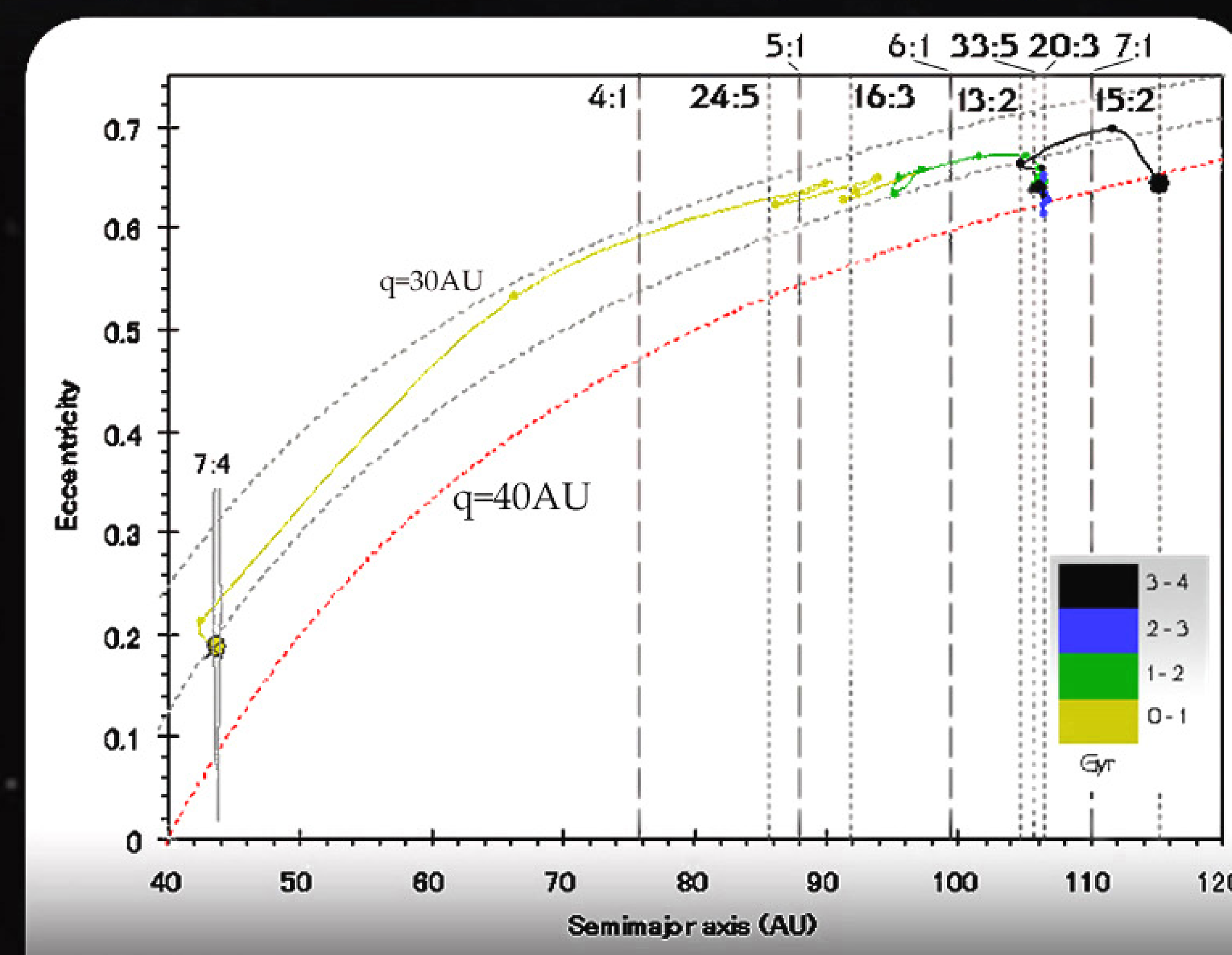

FIGURE 4: A typical example of multiple resonance sticking: temporary captures in the 24:5, 16:3, 13:2, 20:3, 33:5 and 15:2 resonances. Also, this body followed quite well the sticking relation.

Inclination evolution

Determined by the mutual action of scattering and resonance excitation. Typically particles had 10-30°, but others with long resonance trapping reached up to 45°.

Kozai resonance

Approximately 20% of the scattered bodies showed irregular Kozai resonance. We detected it inside the 2:1, 9:1, 15:2, 8:3 and other resonances.

Extended scattered TNOs

- About 5-10% of the survivors in the scattered region had q>40AU for all simulations, even with diverse initial conditions
- The perihelion distances varied from 40AU to about 60AU with semimajor axes typically not exceeding ~250AU
- In general, extremely long residence time in $p{:}1$ or $p{:}2$ resonances (>3Gyr)
- Some extended particles showed Kozai resonance or very slow circulation of the argument of perihelion. This and long-term captures in resonances appear to be good clues for understanding the formation of these bodies (see also the table below)

Group	Scattered bodies proportion	Mean i (°)	Ratio of mean total time spent in resonances to total dynamical lifetime	Proportion of Kozai resonants
30AU<q<35AU	50%	16.7	20%	0%
35AU<q<40AU	40%	16.8	30-40%	13%
q>40AU	<10%	25.2	>80%	50%

TABLE 1: General properties of simulated scattered bodies divided into three groups according to the their final averaged perihelion. Values are statistical approximations.

Conclusions

(1) The formation of scattered objects proceeds in billion year time scales with intermittent scattering and temporary resonance trapping (resonance sticking).

(2) Extended scattered TNOs (perihelion distance q>40AU) are able to form via resonance sticking with two particular conditions:
- more than about 80% of the object's dynamical lifetime spent inside resonance(s)
- trapping in $p{:}1$ or $p{:}2$ resonances (e.g., 3:1, 4:1, 5:2, ...).

This hypothetical mechanism predicts that about 5-10% of current scattered TNOs with semimajor axes a<250AU would possess 40AU<q<60AU. Therefore, this mechanism is not valid for the recently discovered 2003 VB_{12} or "Sedna".

(3) The formation of extended scattered TNOs is apparently independent of initial orbital elements (no preference for the source region). Besides, planetary migration is also not required.

(4) Considering hot initial orbital conditions, it is likely that the classical region (42AU<a<48AU) has been providing members to the scattered region, so that scattered TNOs would consist of primordial scattered bodies mixed with classical ones.

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