MAPPING SURFACE COLORS OF TNOs THROUGH LARGE SURVEYS

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SMALL BODIES IN THE SOLAR SYSTEM

Formation in a Disk

Evolved \(~4\)Gyr

Small bodies Today

- Size Distribution
- Composition
- Dynamics
- Shape

What do we see today and what can we learn about Solar System formation from small body characteristics?
CONSTRaining neptune’s migration:  
the surface composition of trans-neptunian objects

• What are TNOs?
  • How do we discover TNOs?
  • How was the outer Solar System populated?
  • How do we differentiate TNO surfaces?
  • Can we link orbits, migration history, and surfaces to form a coherent picture of the history of the outer Solar System?
The likely primordial, low eccentricity low inclination region of the belt is the Cold Classical TNOs.

Many TNOs have orbits with large eccentricities and inclinations - these are Dynamically excited TNOs.

TNOs trapped in mean motion resonances with Neptune (in phase protected orbits) are Resonant TNOs.
CONSTRAINING NEPTUNE’S MIGRATION: THE SURFACE COMPOSITION OF TRANS-NEPTUNIAN OBJECTS

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**TNO DISCOVERY SURVEYS**

- 948 detected TNOs
- 838 characterized TNOs (brighter than limits)
- only 2 lost in tracking.
- Minor Planet Center has 1083 multi-opposition TNOs
- LSST will detect more TNOs but not fainter.

836 TNOs

the largest fully tracked survey ever made

**Characterized TNO Detections**

- CFEPS: 169
- HiLat: 24
- Alexandersen: 77
- OSSOS: 836

rest: Bannister et al. 2018)

(This is about 30% of all known TNOs!)
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THE NICE MODEL

• Many of the TNOs are emplaced in the outer solar system during a period of planetary migration or instability.

• Many migration models include a dramatic instability, such as a mean motion resonance crossing, which destabilizes the planetary orbits.

• Periods of smooth migration are may also occur, as Neptune migrates slowly outward due to planetesimal scattering.
A period of slow, sweeping migration would also cause the resonances to sweep slowly through the primordial disk.

This sweeping migration can pump particle eccentricity and drag the TNOs outward within the resonances (e.g. Malhotra 1995).
SWEEPING MIGRATION

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![Diagram showing the relationship between eccentricity and semi-major axis over time. The diagram includes a scatter plot with data points representing eccentricity over semi-major axis at different times, highlighting the 2:1 resonance. The plot is labeled: "Time = 0.00e+00 years", "final 2:1 resonance", and credits: "Plot: R. Murray-Clay K. Volk".]
SIGNATURES OF MIGRATION

Figure 4 illustrates the difference in high-perihelion objects in our smooth and fast migration simulations. We first consider a particle within our GS simulation. In panel (A), we plot the ratio of the particle’s orbital period to Neptune’s orbital period against the particle’s perihelion. When the simulation first begins, Neptune is migrating with an e-folding time of 30 Myr, and the particle is scattering off of the ice giants. Consequently, the particle’s period changes rapidly. During this phase, Neptune’s semimajor axis jumps by 0.5 au at 28 au and \( t \approx 30 \) Myr, and Neptune then begins migrating with a slower timescale of 100 Myr. Approximately 20 Myr after Neptune’s jump, the scattering particle is captured in the 5:2 resonance. This capture can be seen in panel (B), as the critical resonant angle begins librating around the 70 Myr mark. Shortly after resonance capture occurs, the particle’s perihelion is driven outward by the Kozai mechanism. Because Neptune is still migrating at this point and the particle’s high perihelion weakens its coupling with Neptune, the particle falls out of resonance at high perihelion. This can be seen with the resumption of resonant angle circulation in panel (C). With the particle out of resonance, Neptune continues to migrate, and the 5:2 resonance leaves the particle behind, frozen at high perihelion and an orbital period slightly less than 2.5 times Neptune’s.

Next, we look at the evolution of a particle from our SmF simulation in panel (C) of Figure 4. Like the previous particle, this one begins by scattering off of the giant planets, and it is also eventually captured in the 5:2 resonance within the first 100 Myr. However, in this particular simulation, Neptune is migrating outward faster. At about \( t \approx 130 \) Myr Neptune has completely finished migrating, and the particle is still in resonance, as indicated by the continued libration seen in panel (D). From this point on, when Kozai cycles drive the particle to high perihelion, its semimajor axis will always remain near the 5:2 MMR since Neptune’s semimajor axis is not evolving. Thus, with faster migration timescales, there is a much shorter opportunity for resonances to develop large fossilized populations of objects that fall out and trail the resonances.

3.1.1. Trailing Population of the 3:1

Of all the resonances that show trailing populations, the 3:1 MMR may be the most useful for several reasons. First, it is well separated from other major MMRs (unlike the 5:2, which is closely flanked by the 7:3 and 8:3 resonances), so there is less chance to confuse the influences of different resonances. Even in the GS simulation, which has the largest resonance trails, it is easy to separate the 3:1 objects from the rest of the high-perihelion Kuiper Belt. In addition, it is well populated in each of our simulations, so a statistically useful distribution of orbits can be attained. Finally, it is closer to the Sun than our other consistently well-populated, well-separated resonance, the 4:1 one, so objects in the 3:1 resonance are about twice as easy to detect according to Sheppard et al. (2016).
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Colors of the Outer Solar System Origins Survey (Col-OSSOS)

rgJgr observations & pilot z-band study
discovery & u band

pilot z-band study

Subaru
CFHT
Gemini

Image Credit: Gemini
Col-OSSOS Photometry

Schwamb et al. 2019 ApJS
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Tegler & Romanishin 2003
Tegler et al. 2003, 2016
Fraser & Brown 2012
Wong & Brown 2017
Terai et al. 2018

z-Band Photometry
Pike et al. 2017, AJ
Fraser & Brown 2012

Pike et al. 2017, AJ

z-Band Photometry
z-Band Photometry

Fraser & Brown 2012

Pike et al. 2017, AJ
CONCLUSION: COLD CLASSICAL SURFACES ARE DISTINCT IN $g$, $r$, $z$
Constraining Neptune’s Migration: Surfaces of Resonant TNOs

*We combine simulations and photometry to constrain Neptune’s migration.*

- We use dynamical simulations of Neptune’s migration to predict the number of cold classicals in the 2:1, for a variety of migration modes of Neptune.
- We selected a complete (magnitude limited) sample of 2:1 resonators from surveys with known discovery biases (OSSOS, Alexandersen, CFEPS, HiLat).
- We use a survey simulator to replicate the survey biases onto our simulation output, so that we can predict how many cold classical surfaces the surveys would have detected if this model is correct.
- We are acquiring photometry of the complete sample of 34 2:1 TNOs using the Large Binocular Telescope.
- Based on the number of cold classical surfaces detected in the 2:1, we provide limits on the distance and speed of Neptune’s migration.
Constraining Neptune’s Migration: Surfaces of Resonant TNOs

- A slow sweeping migration of Neptune pushes the 2:1 resonance across the cold classical belt.
- In this scenario, our sample should contain ~23-40 cold classical surfaces.
- Sweeping about half of the cold classical region: predict 10 cold classical surfaces in our sample.
- No sweeping results in no cold classicals in the 2:1.
• A slow sweeping migration of Neptune pushes the 2:1 resonance across the cold classical belt.

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Observations

- **Planned:** 33 TNOs in the 2:1, \( m_r \leq 24.5 \)
- **2018A:** 5 objects measured
  - LBCR (z), LBCB (g,r)
- **2018B:** 12 objects observed
  - LBCR (r), MODS1 (g,z)
- **2019A:** 5 targets, MODS1+MODS2
- **2019B:** 5 targets, MODS1+MODS2
- We used the Pan-STARRS photometry to determine image zero points
- We measure the TNO photometry using TRIPPy, a custom moving object photometry routine with a pill-shaped aperture

Large Binocular Telescope (LBT) in Mount Graham, AZ

Fraser et al. 2017
RESULTS

- 2018A colors measured
- No cold classical surfaces, rules out smooth slow migration from our simulation at 90% confidence
- 2018B data being analyzed now
- 2019A observing run May 27.
- 2019B some weather loss
- Total: 27 targets observed
The surface colors of TNOs can be used to understand their formation locations and thus constrain their evolutionary histories.

Red Cold Classical TNO surfaces are distinct from dynamically excited TNO surfaces in the combination of $g$, $r$, and $z$-bands.

Photometry in $grz$ can be used to identify TNOs with cold classical surfaces outside the cold classical dynamical region, including trapped in the 2:1 resonance.
FUTURE STUDIES OF TNO SURFACES

• Future studies will require large photometry samples with known selection biases and high SNR in \( g \), \( r \), and \( z \) bands.

• We proposed the FOSSIL survey as a combined TNO and Jovian Trojan search, to use HSC to find and characterize thousands of new Solar System small bodies.

• A large-scale surface color survey is needed to expand the Col-OSSOS color results and map composition of the initial proto-planetesimal disk.