First transneptunian object in polar resonance with Neptune

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Capture in mean motion resonance has been observed in the Solar System for small objects with prograde as well as retrograde orbits of moderate inclinations. However, no example of an object with a nearly polar orbit was known to be in resonance with a planet. In this Letter, we report that the nearly-polar transneptunian object (471325), nicknamed Niku, is in a 7:9 resonance with Neptune, with a mean lifetime in resonance of $16 \pm 11$ million years. While entrance and exit in the 7:9 resonance is caused by close encounters with Neptune the resonant configuration provides a temporary protection mechanism against disruptive close encounters with this planet. The other nearly polar transneptunian objects do not seem to be in resonance with the planets with the possible exception of 2008 KV42, also known as Drac, that has a small chance of being in the 8:13 resonance with Neptune.

Key words: celestial mechanics–comets: general–Kuiper belt: general–minor planets, asteroids: general – Oort Cloud.

1 INTRODUCTION

The presence of small bodies in mean motion resonance is a ubiquitous feature in the Solar System. Most asteroids known to be in resonance have small to moderate inclination $\leq 40^\circ$. They can be part of large populations such as the asteroid belt with its Jupiter resonances or the Kuiper belt and its Neptune resonances. Temporary mean motion resonance capture can also occur such as with Centaurs in the outer planets’ domain. More recently, it was found that mean motion resonance capture with Jupiter and Saturn occurs at large retrograde inclinations (\geq 140\degree) (Morais & Namouni 2013b). One object is even orbiting in the coorbital region of Jupiter with an inclination of 160\degree (Wiegert et al. 2017; Namouni & Morais 2017c). However, small bodies with polar orbits (i.e. with an inclination near 90\degree) have not been observed in mean motion resonance with a planet. This is most surprising as capture in polar resonances is known to have significant likelihood (Namouni & Morais 2015, 2017a). In this Letter, we report that transneptunian object (471325) 2011 KT19, nicknamed Niku is currently in the 7:9 mean motion resonance with Neptune.

TNO Niku (meaning rebellious in Chinese) was identified by Chen et al. (2016) and has an orbital inclination of 110\degree. Another TNO, 2008 KV42 (nicknamed Drac), with orbital inclination 103\degree was identified by Gladman et al. (2009). The origin of TNOs with such high inclinations is a matter of debate. They could be part of a new reservoir in the Kuiper belt (Gladman et al. 2009) or possibly a sub-product of the gravitational sculpting on the extended scattered disk by an hypothetical planet (Batygin & Brown 2016). The fact that these objects can be in mean motion resonances with the planets may provide additional clues on possible formation mechanisms.

In this Letter, we start by reviewing briefly the work on the polar disturbing function (Namouni & Morais 2017b) that we need and then apply it to Niku’s orbit to identify the relevant argument of the 7:9 mean motion resonance with Neptune. We then generate a set of clones of Niku which are consistent with the observation’s covariance matrix in order to analyse the stability and mean lifetime of the resonant configuration. Finally, we assess the likelihood of other nearly polar TNOs being in a resonant configuration and discuss the implications of these results.

2 THE POLAR DISTURBING FUNCTION AND NIKU’S RESONANCE

We have recently developed a disturbing function for nearly polar orbits to help us identify the possible res-
onances and dynamical behaviours at such inclinations (Namouni & Morais 2017b). In general, the disturbing function is a series expansion of the gravitational interaction of two bodies that revolve around the Sun. The problem we faced for polar motion with the classical disturbing function for prograde motion (Murray & Dermott 1999) and its companion for retrograde motion (Morais & Namouni 2013a), widely used in planetary dynamics, is that their expansions are done with respect to nearly coplanar motion or equivalently for a relative inclination near zero. They are therefore not suitable for suggesting the relevant resonant arguments. When looking for resonances, we tend to favour the strongest. Then the classical disturbing function informs us that these are the pure eccentricity resonances of argument \( q \lambda - p \lambda' + (p - q) \sigma \) where \( \lambda \) and \( \lambda' \) are the small body and planet’s mean longitudes and \( \sigma \) the small body’s longitude of pericentre. The force amplitude of such resonances depend only on eccentricity and not inclination hence their strength.

The polar disturbing function shows that for a \( p:q \) mean motion resonance, the possible arguments are:

\[
\phi_{k}^{p,q} = q \lambda - p \lambda' + (p - q) \Omega - k \omega
\]  

(1)

where \( \Omega \) and \( \omega \) are the small body’s longitude of ascending node and argument of pericentre. The integer \( k \) is even if \( p - q \) is even or odd if \( p - q \) is odd. The amplitude of resonant argument (1) is, at lowest order, proportional to \( \varepsilon^{[k]} \) and does not carry an inclination dependence despite the presence of the longitude of ascending node in the argument’s expression. Therefore, at lowest order in eccentricity, the 7:9 mean motion resonance has the possible arguments \( \phi_{k}^{7,9} = 9 \lambda - 7 \lambda' - 2 \Omega - k \omega \) with \( k = 0, k = \pm 2, k = \pm 4 \).

In a preliminary result presented in Namouni & Morais (2017b) based on numerical integration of Niku’s orbit including only the gravitational interaction of the Sun and Neptune moving on a circular orbit we remarked that Niku was likely to be captured in 7:9 mean motion resonances with Neptune (\( k = 4 \) argument).

In order to confirm this result we used MERCURY (Chambers 1999) to integrate the full equations of motion of Niku in 3 setups including: a) the 8 planets using the Bulirsch-Stoer method with accuracy \( 10^{-15} \) over \( \pm 200,000 \) yrs; b) the 8 planets using the Hybrid method (a symplectic integrator that changes to the Bulirsch-Stoer method to resolve close encounters at a distance that we chose as 10 planets’ Hill’s radii) and a time-step of 15 days over \( \pm 50 \) Myrs; c) the 4 giant planets using the Hybrid method with a time-step of 100 days over \( \pm 500 \) Myrs. The last integration period is of the order of Niku’s half life (Chen et al. 2016). We find that in all simulations Niku is indeed in the 7:9 mean motion resonance with Neptune with resonant argument:

\[
\phi_{4}^{7,9} = 9 \lambda - 7 \lambda' - 2 \Omega - 4 \omega .
\]  

(2)

Figure 1 shows the evolution of the barycentric orbital elements obtained by numerical integration of the mean (nominal) orbit from AstDys\(^1\) at epoch JD 2457800.5 (Table 1). The positions and velocities of the planets were obtained from JPL/HORIZONS\(^2\). The blue curves show the evolution in setup c) while the grey and magenta curves (4th left panel) show the evolution of the resonant angle in setups a) and b), respectively. On the \( \pm 200,000 \) yrs timescale the evolution in setups a) and b) are indistinguishable but there are small differences in setup c) probably due to the secular frequencies being slightly different in the simulations with the 4 or 8 planets. Niku’s barycentric semimajor axis is shown together with the location of nearby resonances with the giant planets (1st left panel). The semi-major axis of the barycentric orbit has smaller amplitude oscillations than the Sun-centred one, thus it is more reliable in identifying the proximity to the web of nearby mean motion resonances (Bannister et al. 2016). The closest are the 7:9 resonance with Neptune (red horizontal line) and the 1:18 resonance with Jupiter (black horizontal line) which almost coincide. The \( k = 4 \) argument of the 7:9 resonance with Neptune librates around \( 180^\circ \) with a period of about 40,000 yrs (3rd and 4th left panels). Resonance capture and exit occur due to nudges in semimajor axis caused by close encounters with Neptune (1st, 2nd and 3rd left panels) which may occur when Niku’s distance to the Sun at the nodes, \( r_{\pm} = a(1 - e^2)/(1 \pm e \cos \omega) \), coincides with Neptune’s orbit. Planetary close encounters are thus driven by the secular period of the argument of pericentre, and due to the \( 180^\circ \) shift between the ascending and descending nodes, occur at 4 values: \( \omega = 90^\circ \pm a \) and \( \omega = -90^\circ \mp a \). Niku’s current orbital parameters imply \( a \approx 0 \) i.e. \( \omega \approx \pm 90^\circ \) (Fig. 2) but libration of \( \phi_{4}^{7,9} \) around \( 180^\circ \) protects it from encounters with Neptune closer than 2 Hill’s radii (2nd and 3rd left panels). Indeed, such close encounters may only occur when Niku is near the ascending or descending nodes (\( \lambda \approx \Omega \) or \( \lambda \approx \Omega + \pi \)) and \( r_{\pm} \approx 30 \) AU (i.e. \( \omega \approx \pm 90^\circ \)). Replacing these values into \( \phi_{4}^{7,9} = 180^\circ \pm \Delta \phi \) provides an estimate of the minimum angular distance between Neptune and Niku while the resonance is maintained:

\[
\Omega_{\pm} = \lambda' \approx 180^\circ - \Delta \phi .
\]  

(3)

Hence, a resonance libration amplitude \( 2 \Delta \phi < 320^\circ \) prevents close encounters with Neptune at distances less than 2 Hill’s radii.\(^3\)

We also integrated clones of Niku with the nominal orbit’s parameters from Table 1 but semimajor axis deviated from the nominal value by \( \pm 3.0 \sigma_{a} \). This procedure has been proposed by Gladman et al. (2008) as a check to confirm resonances in the Kuiper belt. Both clones exhibit similar behaviour to the nominal orbit of Fig. 1. Additionally, we performed numerical integrations for \( \pm 500 \) Myrs in setup c) of a set of 100 clones with orbital parameters generated from a multivariate normal distribution with mean equal to the nominal equinoctial orbital elements’ vector and associated covariance matrix both taken from AstDys at epoch JD 2457800.5. All clones are currently in the 7:9 mean motion resonance with Neptune (\( k = 4 \) argument) which further confirms that the resonance is robust. The resonance configuration lasts on average \( 16 \pm 11 \) Myrs and, similarly to the nominal orbit’s integration, the clones’

\(^1\)http://hamilton.dm.unipi.it/astdys
\(^2\)http://ssd.jpl.nasa.gov
\(^3\)A similar procedure is used to estimate the maximum libration amplitude of stable low inclination orbits in resonances but in that case the relevant measure is the angular distance between the TNO’s longitude of pericentre and Neptune’s mean longitude, \( \sigma - \lambda' \), where \( \sigma = \omega + \Omega \) (Malhotra 1996).
capture and exit from the resonance occurs due to close encounters with Neptune. Since Niku’s perihelion (and minimum nodal distance) is currently 23.5 AU, encounters with Uranus occur at distances > 10 Hill’s radii and have negligible effect on the orbit.

3 ARE OTHER NEARLY POLAR TNOS IN RESONANCE?

Table 1 shows the nominal orbital elements of multi-opposition TNOS with $70^\circ < I < 110^\circ$, $a < 100$ AU and $e < 0.9$ listed by the IAU Minor Planet Centre (MPC). We briefly describe the behaviour of the other TNOS in Table 1 with the purpose of assessing if they are in resonance. This study is not intended to be exhaustive.

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**Table 1.** Sun-centred osculating elements of the nominal orbits of multi-opposition TNOS with $110^\circ \geq I \geq 70^\circ$, $a < 100$ AU and $e < 0.9$ at JD 2457800.5 with 1-σ uncertainties both obtained from AstDys. The mean longitude is related to the mean anomaly $M$ by $\lambda = M + \omega + \Omega$. 

| TNO    | $a$ (AU)     | $e$           | $I$ (°)       | $\Omega$ (°) | $\omega$ (°) | $M$ (°)   |
|--------|--------------|---------------|---------------|-------------|--------------|----------|
| (471325) | 35.5895 ± 0.0016 | 0.331647 ± 0.000029 | 110.13335 ± 0.0012 | 243.769738 ± 0.000029 | 322.1991 ± 0.0049 | 30.4301 ± 0.0034 |
| 2008 KV42 | 41.385 ± 0.013 | 0.49005 ± 0.00022 | 103.42415 ± 0.00024 | 260.91036 ± 0.00029 | 133.2999 ± 0.0063 | 334.622 ± 0.017 |
| 2014 TZ33 | 38.3072 ± 0.0041 | 0.754497 ± 0.000025 | 86.005800 ± 0.000078 | 171.788143 ± 0.000033 | 159.02954 ± 0.00084 | 2.67328 ± 0.00043 |
| 2015 KZ120 | 46.0039 ± 0.0053 | 0.818012 ± 0.000020 | 85.556333 ± 0.000054 | 249.987343 ± 0.000018 | 66.26715 ± 0.00081 | 357.64106 ± 0.00044 |
| (127546) | 67.612 ± 0.022 | 0.689297 ± 0.000093 | 77.93897 ± 0.000018 | 90.364258 ± 0.000046 | 28.2126 ± 0.0018 | 5.4153 ± 0.0025 |
| 2010 WG9 | 52.915 ± 0.025 | 0.64529 ± 0.00015 | 70.30809 ± 0.00035 | 92.06994 ± 0.00025 | 293.0287 ± 0.0067 | 10.3002 ± 0.0082 |

![Diagram](image-url)

**Figure 1.** Evolution of Niku’s nominal orbit from Table 1 in setup c). On the left panel: barycentric semimajor axis $a$ with location of the 7:9 resonance with Neptune (red horizontal line) and 1:18 resonance with Jupiter (black horizontal line); distance to Neptune $d$ (in units of the planet Hill’s radii); resonant angle $\phi_{7:9}$ for ±20 Myrs (3th panel) and for ±200,000 yrs (4th panel) in setup a) (grey), b) (magenta) and c) (blue). On the right panel: barycentric orbital elements $e$, $I$, $\omega$, $\Omega$. 

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4 http://www.minorplanetcenter.net
The nominal barycentric semimajor axis of 2008 KV42 is near the 8:13 resonance with Neptune but there is no current libration. The resonant argument \( k = 9 \) of the +3.0\( \sigma_a \) clone librates stably around 180° but the −3.0\( \sigma_a \) clone does not librate in the 8:13 resonance. This precludes confirmation of the resonance according to Gladman et al. (2008). However, we observe that small nudges in semimajor axis due to close encounters with Uranus (the orbit’s perihelion is currently 21.1 AU) and Neptune at distances \( \gtrsim 3 \) Hill’s radii cause temporary libration (10\(^6\) to 10\(^7\) yrs) in the 8:13 resonance (\( k = 9 \) or \( k = 5 \) arguments) for the nominal orbit and all \( \gtrsim 1.5\sigma_a \) and \( < +2.5\sigma_a \) clones. The \( \gtrsim 2.5\sigma_a \) and \( \gtrsim +3.0\sigma_a \) clones exhibit libration (\( k = 9 \) argument) for the entire 10\(^7\) yrs numerical integration duration. A reduction in the uncertainty of the orbit’s semimajor axis which is an order of magnitude larger than that of (471325) should help decide if 2008 KV42 is in resonance or not.

The next two TNOs in Table 1 have the largest eccentricities in our sample and their nodes are currently close to Saturn’s orbit so they exhibit fast diffusion in semimajor axis due to close encounters with this planet. 2014 TZ33 nominal barycentric semimajor axis oscillates around the location of the 7:10 resonance with Neptune, 1:8 resonance with Saturn and 1:20 resonance with Jupiter. The associated resonant arguments exhibit intermittent behaviour which excludes a stable resonance configuration. The intermittency may be caused by interaction between the resonances as well as close encounters with Saturn. Such close encounters eventually cause ejection from the resonances’ vicinity in a few thousand years. 2015 KZ120 has similar behaviour with close encounters with Saturn removing the orbit from the vicinity of the 9:17 resonance with Neptune, 4:15 resonance with Uranus and 1:26 resonance with Jupiter also in a few thousand years.

The semimajor axis and associated uncertainty for the remaining TNOs in Table 1 is the largest in the sample. The nominal orbit of 2010 WG9’s librates intermittently in the 3:7 resonance with Neptune and 1:13 resonance with Saturn. This could be due to interaction between the two resonances and close encounters at distances \( \gtrsim 5 \) Hill’s radii of Uranus, while close encounters with Neptune move the TNO’s semimajor axis out of the present location. Planetary close encounters are driven by the argument of pericentre’s precession timescale of around 10 Myrs. The nominal orbit of (127546) is closest to the 7:23 resonance with Neptune with brief intermittent libration. Close encounters at distances \( \gtrsim 3 \) Hill’s radii with Uranus as well as close encounters with Neptune, both occurring on the argument of pericentre’s precession timescale, cause the orbit’s semimajor axis diffusion.

We did not include in Table 1 a recently discovered nearly-polar TNO, 2017 CX33, as it has been observed for only one opposition. The nominal orbital parameters published on the IAU Minor Planet Centre imply that it would currently experience close encounters with Saturn near the orbit’s descending node hence a stable resonance configuration would be unlikely.

4 CONCLUSIONS

We applied the recently developed disturbing function for polar orbits (Namouni & Morais 2017b) to show that TNO (471325), also known as Niki, is currently in the 7:9 mean motion resonance with Neptune making it the first example of a Solar System object in polar resonance. The resonance configuration lasts on average 16 ± 11 million years and provides a temporary protection mechanism from close encounters with Neptune.

We briefly analysed the possibility that other nearly polar transneptunian objects may be in resonance with the planets. Of these, only 2008 KV42, also known as Drac, has a small probability (~ 1% with the present data) of being in the 8:13 resonance with Neptune. A better determination of the orbit’s semimajor axis, whose current uncertainty is an order of magnitude larger than that of Niki, should help in deciding Drac’s resonant status.

Niki’s nearly polar orbit at the 7:9 resonance is located between the 4:5 and 3:4 resonances with Neptune. The latter are both populated by objects with low inclination orbits (\( I < 20° \)) while the Plutinos in the nearby 2:3 resonance with Neptune have \( I < 40° \) (Gladman et al. 2012). The presence of small objects on polar orbits with angular momenta lying near the Solar System’s invariant plane is intriguing. Those in resonance have an increased protection from disruptive close encounters with the planets. Understanding their origin will help constrain the processes of formation and evolution of the Solar System.

ACKNOWLEDGEMENTS

This work has been funded by grant 2015/17962-5 of São Paulo Research Foundation (FAPESP).

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