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## DISCOVERY OF A NEW RETROGRADE TRANS-NEPTUNIAN OBJECT: HINT OF A COMMON ORBITAL PLANE FOR LOW SEMIMAJOR AXIS, HIGH-INCLINATION TNOs AND CENTAURS

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### ABSTRACT

Although the majority of Centaurs are thought to have originated in the scattered disk, with the high-inclination members coming from the Oort cloud, the origin of the high-inclination component of trans-Neptunian objects (TNOs) remains uncertain. We report the discovery of a retrograde TNO, which we nickname “Niku,” detected by the Pan-STARRS 1 Outer Solar System Survey. Our numerical integrations show that the orbital dynamics of Niku are very similar to that of 2008 KV<sub>42</sub> (Drac), with a half-life of  $\sim 500$  Myr. Comparing similar high-inclination TNOs and Centaurs ( $q > 10$  au,  $a < 100$  au, and  $i > 60^\circ$ ), we find that these objects exhibit a surprising clustering of ascending node, and occupy a common orbital plane. This orbital configuration has high statistical significance:  $3.8\sigma$ . An unknown mechanism is required to explain the observed clustering. This discovery may provide a pathway to investigating a possible reservoir of high-inclination objects.

*Key words:* Kuiper belt: general – Oort Cloud – surveys

### 1. INTRODUCTION

Many primitive bodies exist in the vast regions of the solar system beyond Jupiter, of which the largest population is the trans-Neptunian objects (TNOs). The details of the orbital distribution of the TNOs preserve information about the evolution of the solar system (Levison & Morbidelli 2003; Lykawka & Mukai 2007). Following the evolution of the planetesimal disk, most TNOs were left in low-inclination orbits (Levison et al. 2008). Even scattered-disk objects have typical inclinations less than  $30^\circ$ – $40^\circ$  (Gomes et al. 2005). However, the discovery of 2008 KV<sub>42</sub> (Gladman et al. 2009) revealed the first member of a new population: a retrograde TNO. Dynamical simulations of 2008 KV<sub>42</sub> demonstrate that it has a very long lifetime (a few Gyr; Gladman et al. 2009), suggesting that a large population with similar orbits may exist in this region.

Centaurs are minor planets with semimajor axes between those of Jupiter and Neptune and whose orbits are planet-crossing. They constitute a link between the short-period Jupiter-family comets and the reservoir of icy bodies in the outer solar system (OSS; Levison & Duncan 1997). Centaur orbits are typically unstable, with lifetimes of  $5 \sim 50$  Myr (Volk & Malhotra 2013). Centaurs are generally assumed to originate as scattered-disk objects that interact with Neptune, causing a change in semimajor axis. However, high-inclination Centaurs seem not to originate from the scattered disk (whose inclination distribution seems to be too narrow to supply high-inclination objects such as 2008 KV<sub>42</sub>). Volk & Malhotra (2013) also find that the Kuiper belt is an extremely unlikely source of the retrograde Centaur. Some researchers suggest that the Oort cloud could be the source of such high-inclination

Centaurs (Brasser et al. 2012; Rabinowitz et al. 2013), but given the small number of high-inclination objects in the Minor Planet Center (MPC) catalogs, the origin of the high-inclination population in the OSS will remain uncertain until more such objects are detected and their orbital distribution is understood.

The Panoramic Survey Telescope and Rapid Response System 1 Survey (Pan-STARRS 1, hereafter PS1) is the first wide-field optical system ( $3\pi$  steradians) using a dedicated large-aperture (1.8 m) telescope to carry out multi-epoch, multi-color observations with careful calibration (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013). The PS1 OSS key project has completed an initial search for slow-moving objects, resulting in hundreds of candidates, of which  $\sim 50\%$  are known (Holman et al. 2015). In the catalog of initial results, we identified a distant object with an inclination greater than  $90^\circ$ , i.e., retrograde TNO.

Here, we report the discovery of another retrograde TNO and analyze its dynamical evolution. In addition, after selecting known objects from the MPC database that satisfy the orbital criteria of perpendicular orbits, with the aim of identifying similar objects, we found a population of high-inclination objects that occupy the same orbital plane but that orbit in both senses (retrograde and prograde).

### 2. OBSERVATIONS

The PS1 survey observed the entire sky north of declination  $-30^\circ$  using a Sloan-like filter system ( $g_{P1}$ ,  $r_{P1}$ ,  $i_{P1}$ ,  $z_{P1}$ ,  $y_{P1}$ ). In addition, PS1 observed within  $\pm 20^\circ$  of the plane of the ecliptic using the  $w_{P1}$ -band (limiting magnitude  $\sim 22.5$ , corresponding to TNO  $H \sim 6.5$ ), which spans the wavelength range of  $g_{P1}$ ,  $r_{P1}$ , and  $i_{P1}$ . Upon searching the PS1 for OSS objects, we

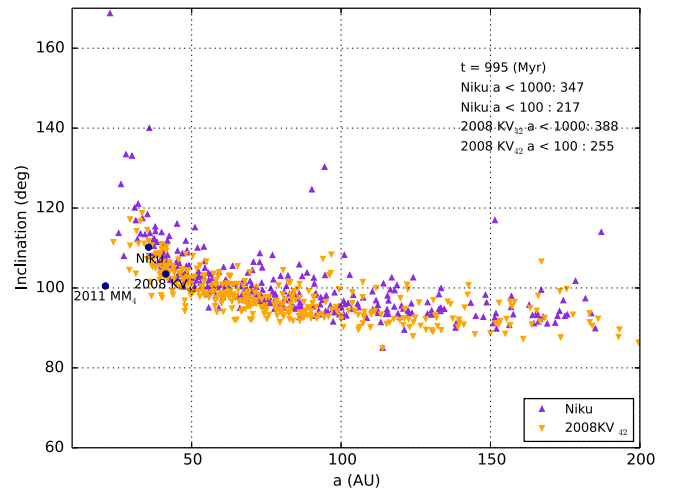
identified an unusual object, which we nicknamed “Niku,” with a retrograde, nearly polar orbit.

Niku has been observed 22 times by PS1 at two different oppositions. To test and improve the orbit determination of Niku, we obtained follow-up observations with the 1-m Lulin Observatory Telescope (LOT) in Taiwan. In addition, we gathered archival DECam and CFHT observations using Solar System Object Image Search<sup>8</sup> (Gwyn et al. 2012). The astrometry and photometry of all observations were calibrated against the PS1 catalog. We determined the orbit of Niku, based on observations spanning four oppositions, using the orbit fitting code of Bernstein & Khushalani (2000). The resulting uncertainties in the heliocentric orbital elements are all small. The elements are inclination  $i = 110^\circ.2929 \pm 0^\circ.0004$ , longitude of ascending node  $\Omega = 243^\circ.8181 \pm 0^\circ.0001$ , semimajor axis  $a = 35.724932 \pm 0.006153$  au, eccentricity  $e = 0.333599 \pm 0.000144$ , and argument of pericenter  $\omega = 322^\circ.593 \pm 0^\circ.015$ . Pericenter passage will occur at  $2451287.350 \pm 1.105$ . The current barycentric distance of Niku is  $25.892 \pm 0.001$ , well inside the orbit of Neptune. We independently verified the orbit determination using the OpenOrb package of Granvik et al. (2009); the results are the same within uncertainty. We note that the orbital elements of Niku are very similar to those of the first retrograde TNO, 2008 KV<sub>42</sub>. Their semimajor axes are both beyond Neptune’s orbit; eccentricities are in the range 0.3 ~ 0.5, and the inclinations of both are larger than 100°.

After we submitted the astrometry of Niku to the MPC, Niku was linked with 2011 KT<sub>19</sub>, an object with a short observational arc (8 days) The initial orbit of 2011 KT<sub>19</sub> was identified as a prograde Centaur (MPEC 2011-L09,  $a = 27.6$ ,  $e = 0.41$ ,  $i = 38.02$ ). The combination of the MPC data for 2011 KT<sub>19</sub> and our observations somewhat improves the orbit determination. However, our observations of Niku alone are good enough to perform a reliable dynamical analysis. Considering the internal consistency of the PS1 reference frame, we use the orbit based on the data measured with the PS1 star catalog for all further analyses.

### 3. NUMERICAL INTEGRATIONS AND ANALYSIS

To explore the evolution of Niku’s orbit in the planet-crossing region, we performed numerical simulations using the MERCURY package (Chambers 1999). We used the covariance matrix generated by the orbit fitting code of Bernstein & Khushalani (2000) and generated 1000 clones drawn from within  $3\sigma$  of the best-fit orbit. We included the four giant planets in the simulations and integrated the 1000 clones forward for 1 Gyr using a 180 day time step. The majority of the clones were stable for at least 0.1 Gyr, with the stable half-life being  $\sim 500$  Myr, with a long tail having lifetimes up to 1 Gyr. The 1000 clones initially had semimajor axes in the range  $35.70 \text{ au} < a < 35.74 \text{ au}$ . During the 1 Gyr simulation, the clones experience orbital evolution, leading to the distribution of *final* semimajor axes illustrated in Figure 1. Twenty percent of clones with a final orbit  $a < 100$  au stably survive beyond 1 Gyr; 30% with  $a < 1000$  au survive beyond 1 Gyr (see Figure 1). This 1 Gyr lifetime is approximately two orders of magnitude larger than a typical Centaur’s lifetime (Volk & Malhotra 2013).



**Figure 1.** Orbital distribution of survivors from 1000 initial clones of Niku (purple) and 2008 KV<sub>42</sub> (orange) after 1 Gyr approximately. The overall clones decay far more slowly than normal Centaurs, with  $>30\%$  of the test particles remaining dynamically stable at the end of a 1 Gyr integration. Note that the orbits of Niku and 2008 KV<sub>42</sub> are located at the highest density position in this plot. Only a few rare clones could evolve to an inclination  $<90^\circ$ . The orbits of selected retrograde objects are also shown.

All survivors exhibited similar orbital evolution: (1) their Tisserand parameter with respect to Neptune is similar ( $-0.1 < T_N < 0.2$ ); (2) most of the clones always have perihelion distances larger than 10 au, where they remain beyond the gravitational influence of Saturn and Jupiter; (3) the integration of 1000 clones of 2008 KV<sub>42</sub>, with the same parameters as above, shows a nearly identical result.

The highest density of survivors in the  $(a, i)$ -plane illustrated in Figure 1 matches the location of Niku and 2008 KV<sub>42</sub>. This may hint at the existence of a large population with a similar origin. We also checked Niku for the existence of resonances with Neptune, i.e., 5:4 (34.9 au) and 4:3 (36.4 au): no libration of resonant arguments was observed.

To understand the relation between Niku and other known objects, we performed the following two analyses. First, we select known objects from the MPC catalog to compare their dynamical evolution with that of Niku. Following the criteria ( $15 < q < 30$ ,  $i > 70$  and  $a < 100$ ) in Brassier et al. (2012) and the perihelion evolution we observed in our Niku clones, we use looser constraints with  $q > 10$ ,  $a < 100$ ,  $i > 60^\circ$ , and opposition  $\geq 2$  to obtain the sample list for understanding Niku’s relation to other similarly inclined objects (Table 1). If the high-inclination reservoir/population mentioned in Gladman et al. (2009) and Brassier et al. (2012) does indeed exist, then we may find some traces from known objects. For the objects in Table 1 with  $a < 100$ , we observe that there is a clustering in the ascending node ( $\Omega$ ) of the objects, regardless of whether the orbit is prograde or retrograde (see Figures 2 and 3). The ascending node of the prograde orbits ranges between  $45^\circ$  and  $95^\circ$ ; the ascending node of the retrograde orbit ranges between  $243^\circ$  and  $282^\circ$ . These two ranges are planar opposite, which means the orbits of these six objects occupy an approximately common plane. Note that the angular momenta of the prograde and retrograde orbits are antialigned. If we change the selection criteria to include all objects with  $q > 5$  and  $i > 60^\circ$ , then we no longer see any obvious clustering in  $\Omega$  (see Figure 2).

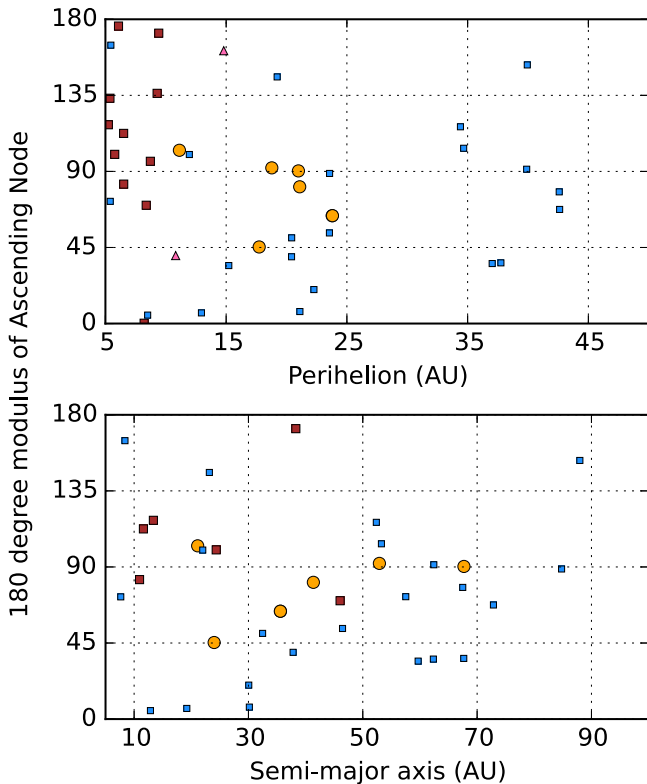
<sup>8</sup> <http://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/ssois/>

**Table 1**  
The Selected High-inclination TNOs and Centaurs

Object	$q$ (au)	$a$ (au)	$e$	$i$ (degree)	Node (degree)	Arg of peri (degree)	$M$ (degree)	$H$ (mag)
Niku	23.81	35.725	0.334	110.3	243.8	322.6	23.8	7.4 <sup>a</sup>
2008 KV <sub>42</sub>	21.11	41.347	0.49	103.5	261.0	133.3	333.1	8.9
2002 XU <sub>93</sub>	21.01	67.734	0.69	77.9	90.3	28.2	4.7	8.0
2010 WG <sub>9</sub>	18.77	52.95	0.645	70.3	92.1	293.1	9.3	8.1
2007 BP <sub>102</sub>	17.73	24.0	0.261	64.7	45.3	125.3	18.6	10.6
2011 MM <sub>4</sub>	11.13	21.126	0.473	100.5	282.6	6.8	41.1	9.3

**Notes.** The orbital parameters are output by the Minor Planet Center and sorted by perihelion distance.

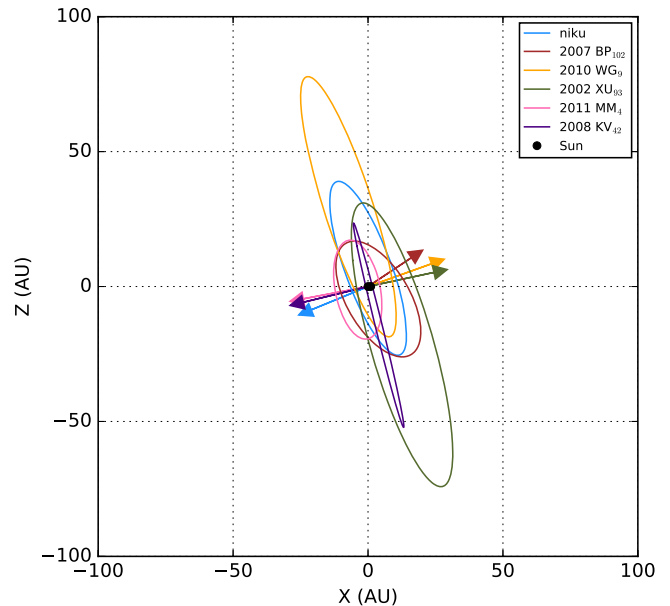
<sup>a</sup> This magnitude is calculated from  $r$  mag.



**Figure 2.** Orbits of known Centaurs and scattered-disk objects, whose inclinations more than  $2\sigma$  ( $36^\circ$ ) away from the dynamically excited cold classical belt. The blue squares indicate the objects with inclination ( $36^\circ < i < 60^\circ$ ). The small perihelion objects ( $q < 10$ ) that remain in the gravitational influence of Saturn and Jupiter are shown as red squares. The triangles represent the objects with large semimajor axis ( $a > 100$ ). And the six objects clustered in a common plane are shown by orange circle.

Second, we performed additional numerical simulations for objects in Table 1. The integrations use the same parameters as described above. We have verified that the clones of 2010 WG<sub>9</sub>, 2002 XU<sub>93</sub>, and 2008 KV<sub>42</sub> could all survive within 1000 au for 1 Gyr, with a survival rate of 16%, 25%, and 38%, respectively. The clones of objects with smaller  $q$  and  $a$  (2007 BP<sub>102</sub> and 2001 MM<sub>4</sub>) have a much smaller probability ( $< 0.5\%$ ) of surviving until the end of the 1 Gyr integration.

We note that the precession directions of the prograde and retrograde orbits are *opposite*. In our integrations, the common plane disappears on a short timescale (a few Myr).



**Figure 3.**  $x$ - $z$  space of selected known objects. The clustering of these six objects in a common plane is obvious. The arrows indicate the directions of the orbital planes. Note that the angular momenta of prograde and retrograde orbits are exactly opposite.

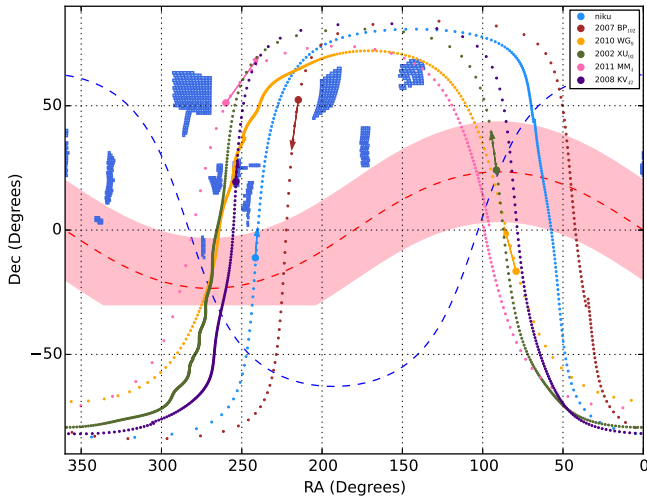
#### 4. DISCUSSION

It is essential to determine the likelihood that the apparent clustering in the longitude of ascending node occurs by chance. Here, we discuss possible reasons for, and origins of, this clustering.

##### 4.1. Coincidence

Because of the small number of samples (only six members), we cannot completely reject the hypothesis that the occupation of a common plane is due simply to coincidence. Using Monte Carlo simulations, we randomly generate six objects with an isotropic  $\Omega$ -distribution ( $0^\circ$ – $360^\circ$ ) and an isotropic  $i$ -distribution ( $0^\circ$ – $180^\circ$ ). Then, these objects are separated into two subgroups, one with  $\Omega \leq 180^\circ$  and one with  $\Omega > 180^\circ$ . Finally, two criteria were defined to decide whether they are in a common plane: (1) the  $\Omega$  of subgroup with  $\Omega < 180^\circ$  are within  $\pm 30^\circ$  of average- $\Omega$  ( $n$ ) of this subgroup, and the  $\Omega$  of another subgroup ( $\Omega > 180^\circ$ ) are within  $n + 180 \pm 30^\circ$ ; (2) the object with  $\Omega < 180^\circ$  has a prograde orbit ( $i < 90^\circ$ ) and





**Figure 4.** Sky path of selected known objects ( $q > 10$ ,  $a < 100$ , and  $i > 60$ ). The arrows indicate the moving directions. The ecliptic plane and galactic plane are shown with dashed lines in red and blue. The blue patches show the survey region of High Ecliptic Latitude Extension with CFHT FOV. The red belt demonstrates the concept region of PS1  $w_{P1}$ -band survey ( $\pm 20$  ecliptic plane and decl.  $> 30^\circ$ ). Note that the PS1  $w_{P1}$ -band survey actually did not cover the full region of the cross section between ecliptic plane and galactic plane. The selected objects show an obvious common plane.

the object with  $\Omega > 180^\circ$  has a retrograde orbit ( $i > 90^\circ$ ). In other words, assume  $n$  is the average- $\Omega$  in the range  $0^\circ < \Omega < 180^\circ$ , and then check the object if ( $n - 30^\circ < \Omega < n + 30^\circ$  and  $i < 90^\circ$ ) or ( $n + 180^\circ - 30^\circ < \Omega < n + 180^\circ + 30^\circ$  and  $i > 90^\circ$ ). After a million iterations, the probability of getting six objects in a common plane is 0.016%, or about  $3.8\sigma$ . Furthermore, the explanation that the common plane is merely a coincidence becomes even more implausible if we consider (a) other orbital parameters and (b) the dynamical behavior of the objects.

Alternatively, one might consider that a distant and inclined primordial disk could be feeding objects into this high-inclination population. However, any clustering of their ascending nodes would likely be erased within a few Myr by the orbital precession discussed in Section 3. At this stage, the small number of known high-inclination objects makes it impossible to attempt to reconstruct the orbital distribution of such a putative distant population.

#### 4.2. Observational Bias

Most of the large surveys that search for moving objects focus primarily on the region close to the plane of the ecliptic, typically within  $\pm 20^\circ$ . The lack of a high ecliptic latitude survey leads to an obvious bias against high-inclination objects. Except for CFEPS and OSSOS, most of the survey data have not had their detection efficiencies thoroughly characterized, though PS1 will be characterized in the near future. A systematic analysis of the expected population is therefore currently impossible. The only *high latitude* survey that has been characterized is the CFEPS High Ecliptic Latitude Extension (CFEPS-HELE; Kavelaars et al. 2008; Petit et al. 2016). The CFEPS-HELE survey detected at least two high-inclination objects, namely, 2009 MS<sub>9</sub> and 2008 KV<sub>42</sub>. We note that 2009 MS<sub>9</sub> does *not* occupy the common plane discussed above, but 2008 KV<sub>42</sub> *does* orbit within this plane. If a survey region only concentrates on a particular R.A. range,

the bias of  $\Omega$  and discovered position will be shown in the sky. Based on the survey regions of PS1 and CFEPS-HELE, we find no obvious bias that can explain the clustering of  $\Omega$  (see Figure 4).

The current version of the pipeline used to generate the catalog of moving object candidates from the PS1 OSS uses a novel heliocentric transformation method to efficiently identify and link observations across multiple nights. This method, to be fully described in M. J. Holman & M. J. Payne (2016, in preparation), requires a heliocentric distance be assumed for the objects under investigation. The assumed distance is then iterated to find the best *approximate* heliocentric distance, before the linked observations are handed off to have a detailed orbital fit generated by the *Orbfit* routine of Bernstein & Khushalani (2000). Crucially, a *minimum* assumed distance of 25 au was used in this initial pipeline run, as a means to ensure rapid progress. However it is likely that this biased the initial pipeline search *against* finding Centaurs and other objects with heliocentric distances significantly less than 25 au. As such, we expect that an imminent update to the PS1 OSS, which expands the parameter space that is searched to well inside 25 au should reveal additional Centaur-like objects, and may well provide additional high-inclination candidates. The combination of well-characterized PS1 and CFEPS-HELE data sets will provide extraordinary means to search for a population at high ecliptic latitudes.

#### 4.3. Planet Nine or Dwarf Planet

As discussed in Sections 3 and 4.1, we expect that orbital precession will quickly erase the occupation of a common plane. Hence, another perturber or mechanism may be required to maintain this occupation. Considering the hypotheses from literature, those postulating external forces, like the hypothetical Planet Nine (Batygin & Brown 2016; Holman & Payne 2016), solar companion (Gomes et al. 2015), and a dwarf planet in a scattered disk (Lykawka & Mukai 2008), all seem to be problematic, as they have great difficulty in affecting the planet-crossing region, due to the small perturbations they exert at such great separations (small tidal parameter,  $M * \text{au}^{-3}$ ). Our mock integrations using the same parameters in Section 3, but inserting the proposed Planet Nine (Batygin & Brown 2016), are *not* able to maintain the common orbital planet of the test particles over any significant timescale, i.e., the orbital precession still erases the  $\Omega$  clustering quickly.

We note that the simulations in Batygin & Brown (2016), provide a source of high- $i$  and large- $a$  TNOs with a clustered distribution of  $\Omega$ . Their cluster has an “X” shape composed of two common planes, and we stress that *neither* of which are coincident with the plane in Figure 3. Moreover, even if the objects that occupy our common plane did somehow originate from this “X” shape, the  $\Omega$  clustering would still be expected to vanish due to precession, and hence some mechanism to confine the orbits would be required.

#### 4.4. Unknown Mechanism or Undetected Dwarf Planet

The high- $i$  Centaurs and TNOs may originate in the Oort cloud (Brasser et al. 2012) or some other undetected reservoir (Gladman et al. 2009), based on the small change of inclination (Volk & Malhotra 2013). As mentioned in Section 4.3, irrespective of origin, the observed clustering in  $\Omega$  still requires a mechanism to maintain the common plane in the face of

divergent orbital precession. The existence of such a mechanism has not been established.

The detailed exploration of such an unknown mechanism is beyond the scope of this letter, but as indicated in Section 4.3, we established through numerical integrations that the putative Planet Nine was unable to explain the orbital confinement. In addition, we also attempted more extreme alternative scenarios, consisting of integrations that include a synthetic high-inclination dwarf planet of a few Earth masses whose orbit crosses the giant-planet region. None of these attempts succeeded in anchoring the  $\Omega$  of the test particles. Moreover, adding a planet into a planet-crossing region has a very high chance of disrupting the orbital structure of the Kuiper belt and remaining OSS.

A more detailed set of investigations is required to understand whether this common orbital plane is dynamically robust and long-lived and, if so, what mechanisms contribute to its longevity. Additionally, it remains to be seen whether the observed common orbital plane survives further observational scrutiny. Well-characterized observations of objects in this plane will also contribute to an understanding of overall observational bias. A deeper and wider survey, such as LSST, may provide a means for detecting additional high- $i$  objects in this common plane and/or an undetected dwarf planet that is sculpting their orbits.

## 5. CONCLUSION

We report the discovery by the Pan-STARRS-1 OSS Survey of a new retrograde TNO. Our numerical integrations of Niku show that its dynamical evolution is very similar to that of 2008 KV42. This result may hint at the existence of a large population of a similar origin.

We have also uncovered the possible occupation of a common plane by the known objects with  $q > 10$ ,  $a < 100$ , and  $i > 60^\circ$ . The mechanism causing and maintaining this common plane is still unknown. The detection of additional high-inclination objects in future surveys, such as PS2 or LSST, will provide additional clues as to the dynamical origin of this population.

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*Facilities:* PS1, CFHT, Blanco, LOT.

*Software:* orfit (Bernstein & Khushalani 2000) and Mercury 6.2 (Chambers 1999).

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