A low-inclination neutral Trans-Neptunian Object in a extreme orbit

Ying-Tung Chen (陳英同)\textsuperscript{1}, Marielle R. Eduardo\textsuperscript{1}, Marco A. Muñoz-Gutiérrez\textsuperscript{1}, Shiang-Yu Wang (王祥宇)\textsuperscript{1}, Matthew J. Lehner\textsuperscript{1,2} and Chan-Kao Chang (章展誥)\textsuperscript{1}

\textsuperscript{1}Institute of Astronomy and Astrophysics, Academia Sinica, No.1, Sec. 4, Roosevelt Rd, Taipei 10617, Taiwan
\textsuperscript{2}Department of Physics and Astronomy, University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19125, USA

ABSTRACT

We present photometric observations and numerical simulations of 2016 SD\textsubscript{106}, a low inclination ($i = 4.8^\circ$) extreme trans-Neptunian Object with a large semi-major axis ($a = 350$ au) and perihelion ($q = 42.6$ au). This object possesses a peculiar neutral color of $g-r = 0.45 \pm 0.05$ and $g-i = 0.72 \pm 0.06$, in comparison with other distant trans-Neptunian objects, all of which have moderate-red to ultra-red colors. A numerical integration based on orbital fitting on astrometric data covering eight years of arc confirms that 2016 SD\textsubscript{106} is a metastable object without significant scattering evolution. Each of the clones survived at the end of the 1 Gyr simulation. However, very few neutral objects with inclinations $< 5^\circ$ have been found in the outer solar system, even in the main Kuiper belt. Furthermore, most mechanisms which lift perihelion distances are expected to produce a very low number of extreme objects with inclinations $< 5^\circ$. We thus explored the possibility that a hypothetical distant planet could increase the production of such objects. Our simulations show that no 2016 SD\textsubscript{106}-like orbits can be produced from three Kuiper belt populations tested (i.e. plutinos, twotinos, and Haumea Family) without the presence of an hypothetical planet, while a few similar orbits can be obtained with it; however, the presence of the additional planet produces a wide range of large semimajor-axis / large perihelion objects, in apparent contradiction with the observed scarcity of objects in those regions of phase space. Future studies may determine if there is a connection between the existence of a perihelion gap and a particular orbital configuration of an hypothetical distant planet.

Keywords: celestial mechanics — surveys — Kuiper belt objects: individual (2016 SD106)

1. INTRODUCTION

Trans-Neptunian Objects (TNOs) are not simply a group of planetesimals that survived after the early evolution of the solar system, but are also a complicated combination of remnants transferred from different locations of the solar system during the planetary migration. TNOs can be broadly classified into dynamically cold and hot populations. The dynamically cold objects (the so-called cold classical Kuiper Belt objects), which observationally congregate at inclinations $i < 5^\circ$ and around semi-major axes $a$ between 39.4 and 47.7 au, are thought to be formed in situ and have survived after the migration of Neptune, whereas many of the dynamically hot objects that spread over a wide range of semi-major axes from 30 to many hundreds au were perturbed/scattered by Neptune, i.e., hot classical Kuiper Belt objects, objects in mean-motion resonances (MMRs) with Neptune and scattered disc objects (SDOs). Additionally, detached objects (DOs) are not in resonance with Neptune, and typically have semimajor axes $a > 47.4$ au, eccentricities $e > 0.24$, and perihelion $q \geq 38$ au. Because the exact boundary between SDOs and DOs are still being investigated, we refer to $q > 40$ and $a > 250$ au TNOs as “extreme” TNOs. DOs are not influenced gravitationally by Neptune or the other currently known giant planets (see the dynamical reviews by Saillenfest (2020) and Gladman & Volk (2021)), and the physical mechanisms that placed the DOs into their current orbits remain undetermined. Such objects likely originated from the SDO population, but they are now totally disconnected from it because their perihelia have been
Surface composition plays another key role in the investigation of the origin of solar system objects. A correlation between color and inclination was found for the population of classical TNOs (Trujillo & Brown 2002). The dynamically cold objects, i.e. cold classical Kuiper Belt objects, which have redder colors, are representative of the primordial bodies formed beyond Neptune’s orbit. In contrast, the dynamically hot objects, including hot classical objects, MMRs, SDOs, and DOs, were formed in different regions of the solar system before being excited during Neptune’s migration, and thus have a wider color distribution. For example, the color distributions of observed plutinos and twotinos (3:2 and 2:1 MMR with Neptune) range from neutral to ultra red. We note that the MMRs and SDOs often experience resonance sticking or Kozai interactions, which change the semi-major axes, eccentricities, and inclinations of TNOs and/or switch them to other resonances, but both interactions are rarely seen for objects with $a > 250$ au. In addition, the Haumea family, the well-known collisional population, has a unique neutral color distribution ($g − r < 0.5$), which is different from the color of other populations. Their neutral surfaces possibly originate from their past collisional history which exposed underlying material (Trujillo et al. 2007; Rabinowitz et al. 2008). Subsequent discoveries with similar surface colors and inclinations support this hypothesis (Brown et al. 2007). To date, very few neutral objects in the outer solar system have been confirmed with $i < 5\degree$.

The Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP)\(^1\) is a deep multi-band imaging survey of 1400 deg.\(^2\) of the sky with the 8-m Subaru telescope (Aihara et al. 2018). Although the main science goals are cosmology and galaxy evolution, its depth and field coverage provide a unprecedented dataset to detect distant/faint objects beyond Neptune. With this dataset, we have discovered 178 TNOs in Deep/UDep field (Eduardo et al., in preparation) and 231 TNOs in Wide fields (Chen et al. 2018) including an extremely neutral DO. Because the cadence of HSC-SSP was not designed for color observations of TNOs, corrections for rotational and phase angle effects could not be made. We thus made additional observations to obtain precise multi-color measurements.

In this study, we present the color estimation of this extreme neutral object, along with the results of simulations of 2016 SD\(_{106}\), (with and without a hypothetical additional planet) to explore its stability and possible origin.

2. OBSERVATIONS

The Dark Energy Survey (DES) team discovered 2016 SD\(_{106}\) and first submitted the observations to the Minor Planet Center (MPC) (Bernardinelli et al. 2022). However, 2016 SD\(_{106}\) was also independently discovered in the HSC-SSP DEEP2-3 Deep field. Data from the HSC-SSP Deep fields include repeated multi-band (grizy) observations at different epochs. The number of measurements in $g$, $r$, and $i$ are 10, 10, and 14, respectively. The HSC-SSP typically finished all observations for a single filter for Deep/UDep fields within one night, then observations for other filters for the same field usually were executed in the same dark run or later runs. The color estimation of 2016 SD\(_{106}\) from HSC-SSP observations shows a neutral color with a very large uncertainty ($g − r = 0.50\pm 0.24$ and $g − i = 0.70\pm 0.23$). However, most moderate/small size TNOs are known to be non-spherical with rotation periods in the range of several hours. The observed cross-sections thus change with time, causing inaccurate color estimates if observations using different filters are not nearly simultaneous. Therefore, we requested and received CFHT Director’s Discretionary Time (DDT) to confirm the color estimate of 2016 SD\(_{106}\). Consecutive observations for color measurements were completed using MegaCam (Boulade et al. 2003) on CFHT within a span of 1.8 hours on 2021 November 2. The observations were conducted using a sequence of filters of the form $r$-$g$-$r$-$i$-$r$-$z$-$r$-$g$-$r$-$i$-$i$-$r$-$z$-$r$, with all observations performed using sidereal tracking. Assuming a uniform surface color and linear variation, this sequence would remove any rotation effects. The astrometry and photometry of the CFHT DDT and HSC-SSP data were calibrated using the Pan-STARRS1 catalog (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013). The photometry was re-measured with the moving-object photometry package TRIPPy (Fraser et al. 2016) using a point spread function of reference stars to generate trailing apertures according to object motion.

Upon completion of the analysis, we measured the color of 2016 SD\(_{106}\) to be $g − r = 0.45\pm 0.05$ and $g − i = 0.72\pm 0.06$, indicating an extreme neutral surface (see Table 1) similar to those of neutral resonant objects (2004 EW\(_{95}\), 90482 Orcus, 2000 O1, 2015 BF\(_{66}\), 2009 SF\(_{119}\), 2015 MN\(_{122}\), and 2005 VV\(_{126}\)).

\(^{1}\) https://hsc.mtk.nao.ac.jp/ssp/

\(^{2}\) https://hsc.mtk.nao.ac.jp/ssp/
and 2004 TV\textsubscript{357}, SDOs (1996 TL\textsubscript{66}), the solar $g - r = 0.45 \pm 0.02$ (Holmberg et al. 2006), and the Haumea Family member (1996 TO\textsubscript{66}) $g - r \sim 0.46 \pm 0.02$ (see Figure 1). Comparing with the color database in Minor Bodies in the Outer Solar System (MBOSS, Hainaut et al. 2012), 2016 SD\textsubscript{106} is the bluest object among all known SDOs/DOs with color measurements. If the peculiar color of 2016 SD\textsubscript{106} implies a high albedo of $p \simeq 0.51$, as the Haumea Family (Ortiz et al. 2017), the estimation of size is $\sim 80$ km; the estimation of size is $\sim 250$ km with general low albedo of $p = 0.05$. Although we do not know the variability of the phase-curve and light curve, the absolute magnitude could be roughly estimated as $H_r = 6.46$. We note that the $g - r (0.45)$ agrees to the other known neutral objects, but $g - i (0.71)$ is higher than typical value ($\sim 0.6$) due to the brighter magnitude on $i$-band. Following the same method in Sheppard (2010), the spectral gradient (SG) based on $g - r$ and $g - i$ is 1.1 and 6.1 percent of reddening per 100 nm, respectively. (We are not reporting the z-band photometry because there are currently too few DOs with such measurements for useful comparisons.)

To minimize the orbital uncertainties, we combine the observations from HSC-SSP, CFHT DDT and DES\textsuperscript{2} for orbital determination. Based on the observations spanning over 8 oppositions, we determined the orbit using the orbit fitting code of Bernstein & Khushalani (2000). The resulting uncertainties in heliocentric orbital elements are all small: $a = 354.23 \pm 0.49$ au, $e = 0.87973 \pm 0.00014$, $i = 4.8080 \pm 0.001^\circ$, longitude of ascending node $\Omega = 219.494 \pm 0.002^\circ$, and argument of pericenter $\omega = 163.032 \pm 0.005$. Pericenter passage will occur at 2464675.363 ± 0.84.

3. NUMERICAL INTEGRATION AND ANALYSIS

With the available astrometric data over eight oppositions, we can accurately estimate the orbital parameters of 2016 SD\textsubscript{106} and determine its long-term stability. Using the covariance matrix output from the orbit fitting code of Bernstein & Khushalani (2000), we generated 1,000 clones within 3σ of 2016 SD\textsubscript{106} best-fit orbit. We then performed 1 Gyr long numerical simulations using the symplectic integrator from the MERCURY package (Chambers 1999), consid-

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
Designations & $q$ & $a$ & $e$ & $i$ & $H$ & $\text{Arc}$ & $g - r$ & $g - i$ & Orbit & Class \\
& (au) & (au) & & (°) & & (days) & & & & \\
\hline
2016 SD\textsubscript{106} & 42.65 & 354.7 ± 0.4 & 0.87 & 4.80 & 6.8 & 2977 & 0.45 ± 0.05 & 0.72 ± 0.06 & extreme & \\
90377 Sedna & 76.36 & 510.3 ± 0.1 & 0.85 & 11.93 & 1.55 & 11418 & 0.85 ± 0.03 & 1.31 ± 0.04 & extreme & \\
474640 Alicanto & 47.29 & 344.4 ± 1.1 & 0.86 & 25.53 & 6.46 & 7736 & 0.69 ± 0.06 & 1.01 ± 0.06 & extreme & \\
2012 VP\textsubscript{113} & 80.43 & 269.2 ± 0.5 & 0.70 & 21.07 & 4.09 & 3028 & 0.70 ± 0.05 & 1.02 ± 0.06 & extreme & \\
2013 SY\textsubscript{99} & 50.08 & 824 ± 32 & 0.93 & 4.21 & 6.7 & 1156 & 0.64 ± 0.06 & 1.10 ± 0.11 & extreme & \\
19308 (1996 TO\textsubscript{66}) & 38.49 & 43.528 ± 0.001 & 0.11 & 27.33 & 4.88 & 13933 & 0.46 ± 0.02 & 0.58 ± 0.02 & Haumea & \\
120216 (2004 EW\textsubscript{93}) & 26.97 & 39.429 ± 0.008 & 0.35 & 29.31 & 6.61 & 7035 & 0.47 ± 0.06 & 0.53 ± 0.09 & 3:2 & \\
90482 Orcus & 30.13 & 39.0971 ± 0.0004 & 0.23 & 20.57 & 2.19 & 25690 & 0.46 ± 0.04 & 0.64 ± 0.06 & 3:2 & \\
2004 TV\textsubscript{357} & 34.50 & 47.715 ± 0.002 & 0.27 & 9.76 & 6.9 & 5607 & 0.47 ± 0.02 & 0.60 ± 0.02 & 2:1 & \\
15874 (1996 TL\textsubscript{66}) & 34.97 & 83.733 ± 0.003 & 0.58 & 23.95 & 5.46 & 9222 & 0.48 ± 0.07 & 0.67 ± 0.10 & SDO & \\
\hline
\end{tabular}
\caption{Orbital elements and colors of selected extreme TNOs and representative objects with neutral color in the outer solar system.}
\end{table}

\textbf{Note}: Except 2016 SD\textsubscript{106}, all orbital elements were taken from: https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html. For DOs, we only selected $q > 40$ objects which have $gri$ color measurements in the literature. Adapting the transformation equations between $BVRI$ and $gri$ in Smith et al. (2002), the $BVRI$ colors of 2016 SD\textsubscript{106} are given by $B - V = 0.66$, $V - R = 0.37$, and $R - I = 0.47$. The * symbol indicates the measurements were transferred from $BVRI$ data.

\textbf{References}: a = Sheppard (2010), b = Trujillo & Sheppard (2014), c = Bannister et al. (2017), d = Perna et al. (2013), e = Sheppard (2012), f = Hainaut et al. (2012)

\textsuperscript{2}https://minorplanetcenter.net/db_search/show_object?object_id=2016+SD106
Figure 1. Left panel: gri colors of 2016 SD\textsubscript{106}, selected extreme TNOs, and objects from Sheppard (2010) and Sheppard (2012), which include most of the dynamically excited TNO populations. The colors of high-perihelion objects mentioned in Bannister et al. (2017) are indicated by triangles, and the solar color is indicated by the yellow star. The dashed lines roughly indicate the different color regions. Right panel: BVRI colors of 2016 SD\textsubscript{106}, the particularly neutral plutino 2004 EW\textsubscript{95} (Perna et al. 2013), and plutinos, SDOs, and DOs from MBOSS (Hainaut et al. 2012). The BVRI color of 2016 SD\textsubscript{106} was transformed from the original Sloan colors using the equations from Smith et al. (2002).

ering the four giant planets, a 180 day initial time-step, and a 10,000 au ejection distance. We found that all clones survived after 1 Gyr, with 91.7\% of them keeping $a < 1,000$ au. The orbital distributions of the clones at three different times (0, 0.1, and 1.0 Gyr) are illustrated in Figure 2. Our results indicate that a diffusive behavior in $a$ dominates the evolution of 2016 SD\textsubscript{106}, which is similar to the behavior of 2013 SY\textsubscript{99} (Bannister et al. 2017). The semi-major axes diffused both inward and outward due to planetary perturbations. The variations in inclination were small on a Gyr timescale, with an oscillating period of $\sim 100$ Myr between 4° and 7°. The change of perihelion distances was very small over time ($\Delta q < 1$ au), compared, e.g. with the few au change found for the semi-stable extreme object 2000 CR\textsubscript{105} (Gladman et al. 2002).

The semi-major axis of 2016 SD\textsubscript{106} is quite close to that of the hypothetical planet (HP) of Brown & Batygin (2021), and the existence of this HP could dramatically change the orbital elements of distant TNOs (Shankman et al. 2017; Bannister et al. 2017). In order to explore possible origins of low-i neutral DOs, we implemented experimental simulations for four dynamical populations with/without the HP from Brown & Batygin (2021): (1) 2016 SD\textsubscript{106} clones in this study, (2) plutinos, (3) twotinos, and (4) Haumea family members, as these populations contain known neutral objects. Plutino and twotino particle distributions were taken from the L7 model of Petit et al. (2011). We used the objects identified as resonant (those showing libration in a 10 Myr interval) in Muñoz-Gutiérrez et al. (2019), totalling 3340 plutinos and 870 twotinos. For the Haumea family, we generated a random set of 2000 objects, within the boundaries $42 \text{ au} < a < 44.5 \text{ au}$, $0.1 < e < 0.2$, and $24^\circ < i < 28.5^\circ$, following Lykawka et al. (2012). The arguments of perihelion, longitudes of ascending node, and mean anomalies, were randomly chosen between 0° and 360° in all cases. We used MERCURY, with an increased initial timestep of 400 d (in order to speed up integrations without loss of precision) and an ejection distance of 20,000 au, to integrate our systems for 1 Gyr. We considered the evolution of particles under the influence of the giant planets, with and without the presence of the HP ($a = 380$ au, $e = 0.21$, $i = 16^\circ$, $\omega = 150^\circ$, $\Omega = 100^\circ$, $M = 6.2$ M\textsubscript{E}) (Figures 3 and 4). We note that the longitude of perihelion of 2016 SD\textsubscript{106} ($\varpi \sim 22^\circ$) lies within the predicted cluster of $\Delta \varpi$, given the orbital configuration of the HP used here.

With and without the HP, over 85\% of the surviving plutinos and twotinos remain within the range of $\Delta a_0 \pm 0.7$ au after 1 Gyr, and a similar fraction of the surviving Haumea family members remain in the range $42 < a < 44.5$ au. The 2016 SD\textsubscript{106} clones with no HP show very little change, but the HP clearly has a significant influence on the
evolution of the 2016 SD$_{106}$ clone orbits. The $i$ and $q$ of particles from the other dynamical populations evolved and spread evenly between $3^\circ$ to $40^\circ$ and 30 to 380 au by the end of the simulation. We note that a population with large $i$ and large $q$ would be significantly harder to detect since the objects spend most of their time at high latitude and larger barycentric distances. Therefore a large population of such objects would be required to result in the detection of 2016 SD$_{106}$. Our results show that the HP does make it possible for particles in various TNO populations to diffuse towards 2016 SD$_{106}$-like orbits. However, such diffusion produces a significant population of large $a$ / large $q$ objects, in apparent contradiction with an identified observational scarcity of objects in this region of the solar system phase-space, i.e. the so-called perihelion gap (Oldroyd & Trujillo 2021).

4. DISCUSSION

The existence of low-$i$ neutral extreme objects has significant implications. The DOs have $a$ and $i$ distributions similar to those of SDOs, except the values of $q$ are large enough to avoid the strong perturbations from Neptune. Scattering processes cannot vary $i$ much since $q$ and the Tisserand parameter relative to Neptune, $T_N$, are almost constant during the scattering process (Saillenfest 2020). Both SDOs and DOs have similar color distributions as shown in Hainaut et al. (2012) and Figure 1. The orbital boundary between SDOs and DOs is not clearly defined, as it may vary by different classification criteria, e.g. Khain et al. (2020), Gladman & Volk (2021) or a stability validation. For example, the well-known neutral SDO, 136199 Eris was classified as DO in MBOSS. However, even if we neglect the classification definition, TNOs still seem to follow the color-inclination correlation. The color-inclination
Figure 3. Heatmaps of the orbital evolution of 2016 SD106 clones and Haumea Family members in simulations with and without the HP. The white cross and green dot show the initial orbit of 2016 SD106 and HP, respectively. The initial orbits in each simulation are overplotted as black dots, while light blue dots show the final distribution of surviving particles after 1 Gyr. The observational q-gap suggested by Oldroyd & Trujillo (2021) is outlined with a red square. The black curve shows the stability limit for distant SDOs as derived by Batygin et al. (2021); above this line in the a-q plane, particles are quickly destabilized and ejected from the solar system.

correlation demonstrated in Peixinho et al. (2015) shows a lack of objects with \(i < 5^\circ\), \(B - R \sim 1.0\), and remains a weaker correlation for all TNOs. The only known object in this study close to these conditions is the plutino 612029 (1995 HM5), with \(i = 4.8^\circ\) and \(B - R = 1.01 \pm 0.2\). Marsset et al. (2019) combined the OSSOS dataset with previously published measurements (including samples in Peixinho et al. (2015)), and investigated the spectral slope (SS) of dynamical hot populations \((i > 5^\circ)\). We note that the definition of the spectral slope (SS) here is different from the spectral gradient (SG) we evaluated for 2016 SD106, although the two values are comparable. In the detached group, only 2003 FZ129 \((a = 61.4\text{ au}, e = 0.38, i = 5.8^\circ, q = 38.0\text{ au})\) shows a moderate-red-to-neutral slope \(9.88\) and an inclination close to \(5^\circ\), although it shows a moderate-red color \(B - R = 1.32 \pm 0.04\). The inclinations of other DOs are larger than \(17^\circ\). The few neutral objects with \(SS < 5\) in both SDOs/DOs all show medium to high inclinations \((1996\ TI_{66}: 23^\circ, 2000\ YC2: 18^\circ, 2000\ PE_{30}: 18^\circ)\). 2016 SD106 is indeed an unique object among the known SDOs and DOs. Although the inclination distribution of the distant TNOs is poorly known due to relatively small numbers and survey biases, most known SDOs/DOs do not cluster on the ecliptic plane, considering that most outer solar system surveys have a bias towards detecting low-\(i\) objects. So the existence of 2016 SD106 constrains the mechanisms by which extreme objects are produced, and may imply that a particular dynamical evolution occurred with a few
extreme objects, producing the special surfaces/orbits which don’t follow the color-inclination correlation found in TNOs.

The following are possible scenarios related to the origin of 2016 SD106:

Kozai resonance in MMR: Considering the Kozai resonance as a mechanism to raise perihelia, Kozai interactions must be coupled with increases of both $q$ and $i$. It is difficult to explain low-i DOs with large $q$. Results in Section 3 show that the possibility of 2016 SD106 coming from a high order MMRs with Neptune is extremely low. The closest possible MMRs to 2016 SD106 are 1:40 ($\sim 351$ au) and 1:41 ($\sim 357$ au), which are too weak to preserve long-lived resonant objects. Some literature also indicate that the resonant mechanism is too weak to produce DOs beyond 250 au, especially for low-i objects (Gallardo et al. 2012; Brasser & Schwamb 2015). Thus the Kozai resonance cannot explain the low $i$ and high $q$ of 2016 SD106. Recent studies also indicate that theoretical models of planetary migration are unlikely to produce high-perihelion ($q > 40$), low-i DOs (Kaib & Sheppard 2016; Pike & Lawler 2017). In addition, the major MMRs beyond Neptune, i.e. plutinos and twotinos, are very stable at present, and Kozai resonance on these major MMRs is unlikely to produce DOs with only the four known giant planets (see Figure 4).

Object diffused from the inner fringe of the Oort cloud: The orbital elements indicate that 2016 SD106 is in the diffusive region and away from the strong scattering region (Duncan et al. 1987; Bannister et al. 2017). 2013 SY$_{99}$, with a larger semi-major axis $a = 824$ au, could be explained with a diffuse behavior of the “inner fringe” of the Oort cloud in a long-time integration (Bannister et al. 2017) for $45 < q < 50$ au and $1000 <$
The diffusion mechanism along with planetary perturbations could produce the population of 2013 SY$_{99}$, initiating from part of SDOs without an additional source of mass. The efficiency of this scenario is still unknown, which is critical to understand if the production of extreme neutral objects from SDOs is possible.

**Analogues to the Haumea family:** The Haumea family is a collisional population which share similar orbital parameters and surface colors. The possible orbital spaces of this family, assuming a reasonable range of impact velocities, don’t cover the region of the detached population (Lykawka et al. 2012), and most of survived particles have $i = 20 \sim 35^\circ$ and $a = 35 \sim 55$ au. The currently known/possible Haumea family members have moderate inclinations ($i \sim 28^\circ$), rather than low inclinations. If an extremely rare collision event happened in the DO region, then neutral objects could be formed in situ, in which case we should expect more neutral DOs to be detected.

**Hypothetical Planet:** Our simulations with a HP showed the possibility to provide a path to bring TNOs to the detached region. This pathway also fills up the observational $q$-gap ($50 \lesssim q \lesssim 65$ au and $0.65 \lesssim e < 1$) suggested by Oldroyd & Trujillo (2021), who also point out that the presence of a HP would produce observable objects within the $q$-gap. Different $q$-gap outcomes are produced with different orbital configurations of the HP, which suggests that a relationship between various dynamical populations, the observational $q$-gap depth, and an HP may exist. Some plutinos, twotinos, and Haumea family members can be influenced by the HP and approach the detached region and inner Oort Cloud. The $i$ and $q$ evolution of these clones lowers their detectability dramatically, like 2013 SY$_{99}$ in Bannister et al. (2017), as the clones spend almost all of their time at higher inclinations and larger perihelia.

2004 EW$_{95}$: Although the high-$i$ plutino hints at a different dynamical evolution, 2004 EW$_{95}$ ($i = 29^\circ$) is the first TNO confirmed with a neutral surface possibly composed by more carbon and silicates (ferric oxides and phyllosilicates) than typical TNOs (Secull et al. 2018). 2004 EW$_{95}$ is thought to have originated closer to the Sun during planetary migration. This object indeed supports the model prediction that a small fraction of objects with carbonaceous surfaces could be resident in the outer solar system. Future spectral observations of 2016 SD$_{106}$ in optical and IR are essential to confirm its surface composition and albedo.

A search of the MPC Database for objects with $a > 250$ and $q > 40$ found that 2013 RA$_{109}$ and 2014 WB$_{556}$ are potentially neutral color objects as well, although their inclinations are moderately high ($12.4^\circ$ and $24.2^\circ$). We emphasize that there may be no significant discrepancy between the neutral color of 2016 SD$_{106}$ and the color-inclination correlation, since this correlation has not yet been fully measured over the different dynamical populations. While the color and orbital elements of 2016 SD$_{106}$ provide valuable tracers of DO formation, more systematic color observations of DOs discovered in future surveys (e.g. LSST) could provide more clues to understand their formation.

5. SUMMARY

Our observations show the low-$i$ extreme TNO 2016 SD$_{106}$ has an unusual neutral color of $g - r = 0.45 \pm 0.05$ and $g - i = 0.72 \pm 0.06$. A numerical integration of clones shows that its orbital evolution over 1 Gyr is stable, with some diffusion behavior. Current dynamical populations with neutral surface members could not easily produce 2016 SD$_{106}$-like objects when only accounting for perturbations due to known planets. Although a HP could provide the possibility for plutinos, twotinos or Haumea family members to migrate towards the extreme region, this mechanism would require a vast population to produce the detection of 2016 SD$_{106}$. This rare neutral object with large-$a$, large-$q$, and low-$i$ provides an additional tracer to understand the origin of extreme objects.
Based on data collected at the Subaru Telescope and retrieved from the HSC data archive system, which is operated by the Subaru Telescope and Astronomy Data Center (ADC) at NAOJ. Also based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. The observations at the Canada-France-Hawaii Telescope were performed with care and respect from the summit of Maunakea which is a significant cultural and historic site. This publication uses data generated via the Zooniverse.org platform, development of is which funded by generous support, including a Global Impact Award from Google, and by a grant from the Alfred P. Sloan Foundation. The Hyper Suprime-Cam (HSC) collaboration includes the astronomical communities of Japan and Taiwan, and Princeton University. The HSC instrumentation and software were developed by the National Astronomical Observatory of Japan (NAOJ), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, the High Energy Accelerator Research Organization (KEK), the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan (ASIAA), and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University.

The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

**Facilities:** CFHT (MegaCam), Subaru (Hyper Suprime-Cam)

**Software:** orbit (Bernstein & Khushalani 2000), TRIPPy (Fraser et al. 2016), MERCURY (Chambers 1999), and NUMPY (Harris et al. 2020).

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