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A DWARF PLANET CLASS OBJECT IN THE 21:5 RESONANCE WITH NEPTUNE

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ABSTRACT

We report the discovery of a $H_r = 3.4 \pm 0.1$ dwarf planet candidate by the Pan-STARRS Outer Solar System Survey. 2010 JO₁₇₉ is red with $(g-r) = 0.88 \pm 0.21$, roughly round, and slowly rotating, with a period of 30.6 hr. Estimates of its albedo imply a diameter of 600–900 km. Observations sampling the span between 2005–2016 provide an exceptionally well-determined orbit for 2010 JO₁₇₉, with a semi-major axis of 78.307 ± 0.009 au; distant orbits known to this precision are rare. We find that 2010 JO₁₇₉ librates securely within the 21:5 mean-motion resonance with Neptune on hundred-megayear time scales, joining the small but growing set of known distant dwarf planets on metastable resonant orbits. These imply a substantial trans-Neptunian population that shifts between stability in high-order resonances, the detached population, and the eroding population of the scattering disk.

Keywords: Kuiper belt objects: individual (2010 JO₁₇₉)

1. INTRODUCTION

Dwarf planets in the trans-Neptunian region are remnant planetesimals from the protoplanetary disk of the Solar System. They constrain the large-diameter end of the trans-Neptunian object (TNO) size distribution, which is inferred from the observed luminosity function (Petit et al. 2008; Brown 2008; Schwamb et al. 2013; Fraser et al. 2014). However, few are yet known:¹ 33 with absolute magnitude $H_V < 4$.

TNOs are faint due to their > 30 au heliocentric distances, requiring discovery surveys by > 1 m aperture wide-field optical telescopes. Past wide-area surveys have completed the inventory of bright TNOs to $m_r \sim 19.5$ outside the galactic plane (Tombaugh 1961; Kowal 1989; Sheppard et al. 2000; Trujillo & Brown 2003; Moody 2004; Brown 2008; Brown et al. 2015). Substantial areas of sky have been surveyed to $m_r \sim 21.5$ and deeper (Larsen et al. 2001, 2007; Elliot et al. 2005; Schwamb et al. 2010; Sheppard et al. 2011; Petit et al. 2011; Rabinowitz et al. 2012; Sheppard & Trujillo 2016; Petit et al. 2017; Gerdes et al. 2017).

As often the brightest and thus easiest to detect of the worlds in the trans-Neptunian region, dwarf planets also provide a useful broad-brush indication of the phase space of their dynamical populations. They are key to exploring the fainter, large-semi-major-axis populations where the smaller TNOs are too faint to detect; for example, the 2003 discovery of (90377) Sedna indicated a substantial population of TNOs with large perihelion distances (Brown et al. 2004). The $a \gtrsim 50$ au populations are all defined by their degree of gravitational interaction with Neptune: they include orbits librating in high-order mean-motion resonance; the scattering disk, on orbits actively interacting with Neptune; and the “detached” TNOs, with perihelia $q \gtrsim 37$ au (Gladman et al. 2008). Recent discoveries include the 9:2 mean motion resonant object 2015 RR₂₄₅ with $H_r = 3.6$ and $a = 81.86 \pm 0.05$ au (Bannister et al. 2016a), the scattering disk TNO 2013 FY₂₇ with $H_V = 2.9$ and $a = 59$ au (Sheppard & Trujillo 2016), and the detached TNO 2014 UZ₂₂₄ with $H_V = 3.5$ and $a = 109 \pm 7$ au (Gerdes et al. 2017).

The Panoramic Survey Telescope and Rapid Response System 1 Survey (Pan-STARRS 1, hereafter PS1) is well suited to the discovery of TNOs. PS1 is a 1.8 m telescope on Haleakela in Hawai‘i, with a dedicated $0''.258$ pixel, 7 deg^2 optical imager (Kaiser et al. 2010; Chambers et al. 2016). The PS1 3π survey (Magnier et al. 2013; Chambers et al. 2016) repeatedly observed the sky north of Decl. -30° using a Sloan-like filter system (Tonry et al. 2012), reaching typical single-exposure 5σ depths of $g_{P1} = 22.0$, $r_{P1} = 21.8$, and

$i_{P1} = 21.5$ (Chambers et al. 2016, Table 11). PS1 also observed within $\pm 20^\circ$ of the ecliptic using the wide w_{P1} filter ($m_{5\sigma} \sim 22.5$). The observing cadence of PS1 is optimized for detection of inner Solar System minor planets, using the PS Moving Object Processing System (MOPS) (Denneau et al. 2013). However, PS1’s many visits permit detection of slower-moving ($\sim 3''/hr$) TNOs in the accumulated data. Weryk et al. (2016) reported several hundred centaurs and TNOs from a search of the 2010 Feb 24 to 2015 July 31 PS1 observations, which linked together detections within 60-day intervals.

The PS1 Outer Solar System (OSS) key project uses a novel linking solution, based on transforming topocentric observations to a heliocentric coordinate frame using an assumed heliocentric distance. Our initial search of the 2010–2014 PS1 observations resulted in hundreds of candidates, $\sim 50\%$ of which were newly discovered TNOs (Holman et al. 2015). These include unusual objects such as the highly-inclined centaur (471325) 2011 KT₁₉ (Chen et al. 2016), as well as numerous new Neptune trojans (Lin et al. 2016).

Here we report the discovery of a $m_r \sim 21$ dwarf planet candidate at a barycentric distance of 55 au: 2010 JO₁₇₉. We present the technique used to detect 2010 JO₁₇₉ (§ 2), our observations (§ 3), 2010 JO₁₇₉’s physical properties (§ 4), the dynamical classification of its orbit (§ 5), and the broader implications of its existence for our understanding of the distant, dynamically excited TNO populations (§ 6).

2. TNO DISCOVERY TECHNIQUE

We developed our discovery pipeline to cope with the temporal sparsity of the Pan-STARRS data (see Brown et al. 2015 for an independent, alternative approach to detecting TNOs in sparse data sets). Our pipeline operates on the catalogs of source detections found in the direct, undifferenced PS1 exposures spanning 2010 to mid-2014 by the Image Processing Pipeline (IPP) (Magnier 2006, 2007). We eliminate any detection that coincides within $1''$ of a known stationary source. (A catalog of stationary sources was developed from the individual detections in the PS1 exposures; detections that occur near the same location over multiple nights are considered to be stationary.) The remaining transient detections form the input to the rest of the pipeline (we do not use MOPS). We iterate over a set of heliocentric distances, $d \sim 25 - 1500$ au. For each assumed distance, we carry out a number of steps. First, we transform the topocentric sky plane positions of transient sources we identify in the PS1 imaging to those as would be observed from the Sun. Then, all *tracklets* are identified: these are sets of ≥ 2 detections from the exposures within each individual night that are consistent with linear motion that would be bound to the Sun. No minimum rate of motion is required. Tracklets with three or more detections are much more likely to be real, as the

¹ http://www.minorplanetcenter.net/db_search: $a \geq 30$, $q \geq 30$ and $H_V \leq 4$, as of 15 August 2017

positions of their constituent detections must be consistent with linear motion at a constant rate. For every pair of high-confidence tracklets (≥ 3 detections) that can be associated with a bound heliocentric orbit, we look for additional supporting tracklets along the great circle defined by those two tracklets. If an additional tracklet is found, an orbit is fit (using modified routines from the Orbit package of [Bernstein & Khushalani \(2000\)](#)) to the set of observations from those three tracklets, and a search is carried out for additional tracklets along the sky plane trajectory defined by that orbit. As tracklets are found, the orbit is refined and the search continues, recursively. The algorithm is not greedy; all the different linking possibilities are followed until the set of plausibly connected tracklets is exhausted. As a final step, single detections that lie within $1''0$ of the sky plane are searched for and incorporated, with astrometric and photometric outliers rejected.

We consider for further investigation any arc of tracklets with detections on at least five separate nights, that has an orbital solution with a reduced chi-squared $\bar{\chi}^2 \lesssim 3$, and that has a range of observation magnitudes that is physically realistic ($\Delta m_w < 1.5$). All directions of motion of the resulting orbit are permitted and retained.

3. OBSERVATIONS

The observations of 2010 JO₁₇₉ span twelve oppositions. All available photometry is tabulated in Appendix A (Table 3); the astrometry is listed at the Minor Planet Center².

We initially detected 2010 JO₁₇₉ in *g*, *r*, and *i*-band observations spanning 2010–2012 from the PS1 3π survey (Table 3). The absence of *w*-band observations is due to 2010 JO₁₇₉'s 32° ecliptic latitude at the time of discovery, outside the coverage of the PS1 *w*-band survey. 2010 JO₁₇₉ is seen on 12 distinct nights with a total of 24 detections, forming an arc spanning 790 days. 2010 JO₁₇₉ was retained as a candidate TNO as it passed two tests: a) the residuals to an orbital solution determined with a modified version code of [Bernstein & Khushalani \(2000\)](#) were consistent with the astrometric uncertainties of the individual detections ($\sim 0''1$), with no outliers; b) the photometric measurements from the PS1 IPP, transformed to *w*-band ([Tonry et al. 2012](#)), spanned only 1.2 magnitudes. We visually examined the detections in the PS1 images for final verification. The photometry in Table 3 is calibrated to PS1 Data Release 1 (PS1-DR1; [Magnier et al. 2016](#)) and was measured with the moving-object photometry analysis package TRIPPy ([Fraser et al. 2016](#)).

Although 2010 JO₁₇₉ is substantially brighter than the PS1 detection limits, there is a significant bias against finding such objects with the algorithm we described in § 2. First, we note that only two tracklets with three or more detections

can be seen in Table 3. This is the minimum number for our algorithm. If either of these tracklets was removed from the data set, the algorithm would not have found 2010 JO₁₇₉. This could occur moderately often, given the 76% fill factor of the focal plane ([Chambers et al. 2016](#)). Interestingly, the later of those two tracklets was *accidental*: it was found in the overlap between two adjacent fields for which pairs of observations were being taken. The overlap region is 10-20% of the survey area, depending upon the specific survey pattern.

We followed up 2010 JO₁₇₉ with Sloan *r*-band observations on 2016 July 28–30 with the EFOSC2 camera on the New Technology Telescope (NTT; [Buzzoni et al. 1984](#); [Snodgrass et al. 2008](#)) atop La Silla, Chile. EFOSC2 uses a LORAL 2048×2048 CCD which was used in 2×2 binning mode. Each binned pixel maps onto an on-sky square $0''24$ on the side, for a full field of view $4.1' \times 4.1'$. The data were subject to standard bias-subtraction and flat-fielding procedures, and the magnitude of 2010 JO₁₇₉ in each frame was measured using circular aperture photometry and calibrated to PS1-DR1 using tens of field stars.

2010 JO₁₇₉ is bright enough to be found in archival images with the SSOIS search tool ([Gwyn et al. 2012](#)). We recovered astrometry of 2010 JO₁₇₉ from the *griz* observations of a sequence of 54 s exposures (*riuzg*) made on 2005 May 11. The observations by the 2.5 m telescope of the Sloan Digital Sky Survey (SDSS) in New Mexico were part of SDSS-II ([Abazajian et al. 2009](#)). The astrometry of the $0.''396$ pixel images is calibrated to SDSS Data Release 14 ([Abolfathi et al. 2017](#)). The TNO was close by stars, which prevented photometric measurements.

We also found via SSOIS that 2010 JO₁₇₉ was serendipitously imaged in Sloan *g*, *r* and *z* on 2014 August 16–18 by the DECaLS survey³ with the Dark Energy Camera (DECam; [DePoy et al. \(2008\)](#)) on the 4 m Blanco Telescope in Chile. DECam has $0.''263$ pixels with a 3 deg^2 field of view. The DECaLS astrometry and photometry zeropoints are calibrated⁴ to PS1 DR1. Photometry, Point-Spread Function (PSF) modelling, and trailed PSF removal were performed with TRIPPy (Table 3). No evidence of binarity was found. The five highest signal-to-noise (SNR) and best seeing DECam images are our overall highest-SNR images of 2010 JO₁₇₉.

4. PHYSICAL PROPERTIES OF 2010 JO₁₇₉

The mean colors of 2010 JO₁₇₉ were calculated from the mean magnitudes in each band, after correction to unit heliocentric and geocentric distance (Fig. 1). Standard deviations for each band were combined in quadrature to yield the uncertainty. Table 1 summarizes the derived color mea-

² Future citation to the URL of 2010 JO₁₇₉'s discovery MPEC.

³ <http://legacysurvey.org/decamls/>

⁴ <http://legacysurvey.org/dr3/description/>

surements. The substantial time between observations means rotation could have let potential surface variability intrude (Fraser et al. 2015; Peixinho et al. 2015), so we avoid presenting the colors as a coarsely sampled spectrum. The $g-r$ and $r-i$ of 2010 JO₁₇₉ fall along the locus of the known range of TNOs (e.g. Ofek 2012), classing it as moderately red⁵.

The visual albedos constrained by thermal measurements for $2 < H_r < 4$ TNOs are wide-ranging, varying from $p = 0.07-0.21$ (Brucker et al. 2009; Lellouch et al. 2013; Fraser et al. 2014). 2010 JO₁₇₉'s red $g-r$ color places it among TNOs that have albedos at the higher end of this range (Lacerda et al. 2014; Fraser et al. 2014). At $H_r = 3.44 \pm 0.10$ (see below), 2010 JO₁₇₉ has a diameter of at least 600 km; at the less reflective albedo limit, it could be as large as 900 km.⁶ It will thus achieve ellipsoidal hydrostatic equilibrium (Tancredi & Favre 2008; Lineweaver & Norman 2010).

2010 JO₁₇₉'s $r-z$ color is unusual. To make it consistent with the range of $r-z$ colors exhibited by other TNOs with similar $g-r$ colors as 2010 JO₁₇₉ (Pike et al. 2017b) requires a 1σ deviation in both $g-r$ and $r-z$, or a 2σ deviation in either. Yet the mean $r-z$ is consistent with the only single-epoch $r-z$ measurement (from DECam; see Table 1). Alternatively, the negative $r-z$ color is broadly consistent with the presence of methane ice, which exhibits an absorption feature through the z -band (see for example Tegler et al. 2007). For 2010 JO₁₇₉ to have a methane-bearing surface would be unusual, as it is expected that objects of this size would rapidly lose that volatile to space on short timescales (Schaller & Brown 2007), in contrast to the larger dwarf planets; e.g. (50000) Quaoar and 2007 OR₁₀ are red methane-covered objects (Schaller & Brown 2007; Brown et al. 2011).

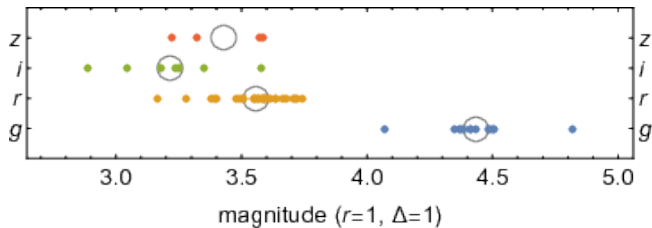


Figure 1. 2010 JO₁₇₉ magnitudes in each band corrected to unit heliocentric and geocentric distance. Gray circles indicate mean magnitudes.

We use the photometry in Table 3 to constrain the color, phase curve and lightcurve properties for 2010 JO₁₇₉. The apparent magnitudes were first corrected to unit heliocentric (r) and geocentric (Δ) distance by subtraction of $5 \log(r\Delta)$.

⁵ Relative to solar color $g-r = 0.44 \pm 0.02$: sdss.org/dr12/algorithms/ugrizvegasun/

⁶ We note that the mass of 2010 JO₁₇₉ is too low to be producing the warp in the mean plane of distant KBOs found by Volk & Malhotra (2017).

Table 1. Optical colors of 2010 JO₁₇₉

Facility	<i>MJD</i>	<i>g-r</i>	<i>r-i</i>	<i>r-z</i>
Mean				
All		0.88 ± 0.21	0.34 ± 0.26	0.13 ± 0.22
Single-epoch				
PS1	55711.36	1.2 ± 0.12		
DECam	56886.00			-0.09 ± 0.25
NTT	57597.13	0.95 ± 0.13		
NTT	57599.01	0.85 ± 0.04		
NTT	57599.04	0.74 ± 0.04		
NTT	57599.08	0.78 ± 0.03		

NOTE—For computation of mean color, see text in § 4.

The corrected g and r magnitudes were fit simultaneously with the following model, which accounts for a linear phase darkening and sinusoidal lightcurve variation,

$$H_{g,r} - (g-r) + \beta\alpha + \frac{\Delta m}{2} \sin \left[\frac{2\pi(t-t_0)}{P} \right], \quad (1)$$

where $H_{g,r}$ is the absolute g or r magnitude, α is the phase angle, β is the linear phase function slope, Δm , P and t_0 are the peak-to-peak variation, period, and offset of the lightcurve, respectively, and $(g-r)$ is a color term subtracted from the g magnitudes only. As is the case for Earth-based TNO observations, the range of phase angle is limited: $0 < \alpha \lesssim 1^\circ$. We found the best-fit β to be somewhat dependent on the initialization values for P , Δm , and β . To solve this, we varied $(g-r)$ linearly in steps of 0.01 mag and at each step generated 200 uniformly distributed random initial values $P \in (16, 64)$, $\Delta m \in (0.15, 0.60)$, and $\beta \in (0.01, 0.50)$. The range of β values brackets the slopes seen in TNOs (Rabinowitz et al. 2007). The NTT r band photometry displays a steady brightening by about 0.2 mag over a period of 5 hours, which provides useful limits on the lightcurve variation ($\Delta m > 0.2$ mag) and period ($P > 10$ hr). We found consistently that shallow phase functions ($\beta < 0.05$ mag/deg) fit the data best (see Fig. 2). For this reason we decided not to correct the data for phase effects before the lightcurve analysis.

We employed the Lomb-Scargle algorithm (Press & Rybicki 1989) to measure the lightcurve period using the r band measurements only. The periodogram identified the period

$P_1 = 30.6324$ hr as the best solution, which corresponds to a single-peaked lightcurve, with one maximum and one minimum per rotation. Figure 3 shows the data phased with P_1 . The double period $P_2 = 2P_1 = 61.2649$ hr is also shown for comparison, in case 2010 JO₁₇₉ has a symmetric lightcurve.

Both the solutions are consistent with the data and indicate that 2010 JO₁₇₉ is a slow rotator. The single-peaked solution, $P \sim 30.6$ hr, would imply that 2010 JO₁₇₉ is roughly spherical and has significant albedo patchiness. The double-peaked solution would imply an ellipsoidal shape with axes ratio $a/b > 1.58$. We find this less plausible, given the large size and slow rotation of 2010 JO₁₇₉.

Finally, the lightcurve period solutions were used to refine the phase curve, resulting in the linear solution shown in Fig. 2, with $\beta = 0.02$ mag/deg. We force $\beta > 0$ in our fitting algorithm, which sets the lower limit on the phase function slope, and find a $1-\sigma$ upper limit $\beta < 0.07$ deg/mag. We find an absolute r magnitude $H_r = 3.44 \pm 0.10$ and a best-fit color offset $g-r = 0.85$, consistent with the $g-r$ values in Table 1.

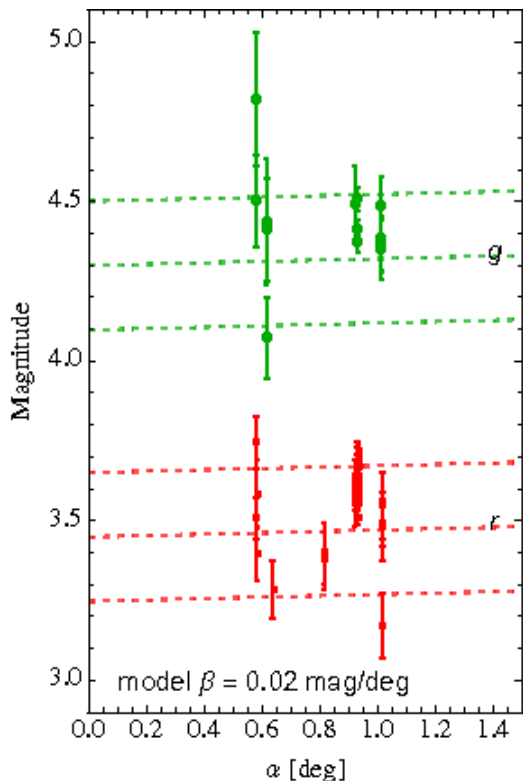


Figure 2. Linear phase curve models for 2010 JO₁₇₉. The slope $\beta = 0.02$ mag/deg ($\beta < 0.07$ mag/deg, $1-\sigma$) was fit simultaneously to the g and r photometry (Table 3). The dashed lines mark the mean brightness and extent of the variation due to the lightcurve (see Fig. 3).

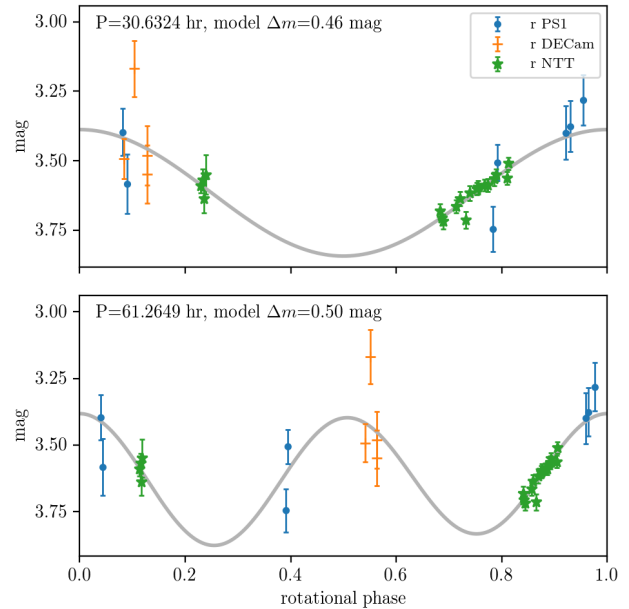


Figure 3. Lightcurve of r -band photometry of 2010 JO₁₇₉, color-coded by observing facility (Table 3). The single-peaked model implies a nearly spherical shape with a patchy surface spinning with a period $P \approx 32.5$ hr. The corresponding double-peaked solution (period $P \approx 65$ hr) implying an ellipsoidal shape with axes ratio $a/b > 1.58$ is less plausible, due to the large material strength required to hold the shape against the crush of gravity.

We determine the barycentric elements of 2010 JO₁₇₉ by fitting observations from six oppositions spanning 2005–2016 (Table 2), using the code of Bernstein & Khushalani (2000). The barycentric distance to 2010 JO₁₇₉ at discovery in 2010 is 55.019 ± 0.003 au.

Table 2. : Barycentric osculating elements of 2010 JO₁₇₉ in the International Celestial Reference System at epoch 2455327.1.

a (au)	e	i ($^\circ$)	Ω ($^\circ$)	ω ($^\circ$)	T_{peri} (JD)
78.307	0.49781	32.04342	147.1722	9.824	2433937.1
± 0.009	± 0.00005	± 0.00001	± 0.0002	± 0.005	± 0.8

NOTE—Best-fit orbit to the arc of observations 2005–2016 with the method of Bernstein & Khushalani (2000), with 1σ uncertainty estimates from the covariance matrix.

We generate 100 clones of the orbit of 2010 JO₁₇₉, varying the observations by their respective uncertainties and re-fitting the orbit, hence creating a statistically rigorous bundle of orbits which are all consistent with the observations. We integrate the best-fit orbit and clones as test-particles in a barycentric system, orbiting in the gravitational field of the

Sun and four giant planets. We integrate the particles using the adaptive IAS15 integrator (Rein & Spiegel 2015) in the REBOUND code of Rein & Liu (2012) for 700 Myr, i.e. around 10^6 orbits of 2010 JO₁₇₉.

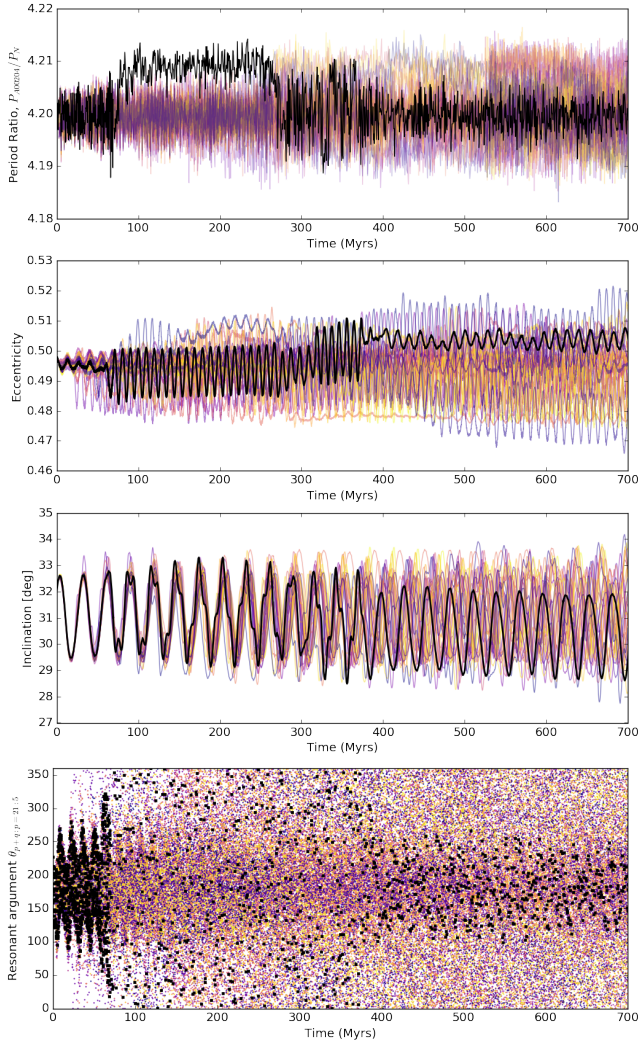


Figure 4. Dynamical evolution of the best-fit orbit for 2010 JO₁₇₉ (black) and clones (colors) sampled from the covariance matrix of the orbital uncertainties. **Top:** Period ratio with Neptune; **2nd:** Eccentricity; **3rd:** Inclination; **Bottom:** Resonance angle, $\theta_{p+q;p=21:5}$ (see Eqn 2). The best-fit orbit stably librates in the 21:5 resonance with Neptune for ~ 70 Myr, before diffusing to a circulating state, and then back to librating. The clones exhibit behavior consistent with that of the best-fit orbit, switching between resonant and non-resonant configurations on ~ 100 Myr timescales, with a slow diffusion away from resonance, such that at 700 Myr, $\sim 25\%$ remain in resonance.

The period ratios with Neptune, eccentricity and inclination for the best-fit orbit (black) and a sample of the clones (all other colors) are shown in the top three panels of Figure 4. All of the particles stably orbit with period ratios very

close to 4.2. We then consider the resonant angle,

$$\theta_{p+q;q} = (p+q)\lambda_{out} - p\lambda_{in} - q\varpi_{out}, \quad (2)$$

and plot in the lower panel of Figure 4 values for Eqn. 2 using $p+q : p = 21 : 5$. The best-fit orbit exhibits stable libration in the 21:5 resonance for ~ 100 Myr before diffusing to a circulating configuration with a period ratio ~ 4.21 with respect to Neptune for ~ 300 Myr, before returning to a 21:5 resonant configuration for the remainder of the simulation. We note that 16 possible resonant angles exist for the 21:5 resonance in which the $-q\varpi_{out}$ term in Eqn. 2 is replaced by $-(n\varpi_{in} + (q-n)\varpi_{out})$, with $0 \leq n \leq 15$. We examined all such variations for all best-fit and clone orbits, and found that only the $n = 0$ case (i.e. Eqn. 2) ever exhibits resonance.

The clones of the orbit of 2010 JO₁₇₉ display behavior consistent with that of the best-fit orbit. For the entirety of the simulation, all clones have period ratios with Neptune that remain bounded between 4.185 and 4.215 (semi-major axes bounded between ~ 78.1 au and ~ 78.5 au) and have pericenters in the range 37.5–41.5 au. Most clones move back and forth between resonant and non-resonant configurations, with a slow overall diffusion away from resonance. All clones are resonant at the start of the simulation, and $\sim 6\%$ remain resonant for the entire simulation. The median time at which clones exit resonance is ~ 110 Myr. At 700 Myr, $\sim 25\%$ of clones are resonant.

The behavior of the best-fit orbit and its clones over the 700 Myr simulation shows that 2010 JO₁₇₉ has a metastable orbit, which switches between resonant and non-resonant configurations on hundred-Myr timescales.

6. DISCUSSION

Although 2010 JO₁₇₉ is bright for a TNO at $m_r \sim 21$, its 32° orbital inclination and resulting current $\sim 30^\circ$ ecliptic latitude is responsible for it not being detected earlier. It is bright enough to have been detected by the surveys of Larsen et al. (2007) and Schwamb et al. (2010), but fell just outside their sky coverage. It was not detected by Weryk et al. (2016), presumably either because 2010 JO₁₇₉ is outside of the region considered in that search, or it was not observed with their required cadence. 2010 JO₁₇₉ is thus a good example of how the detection efficiency of a survey is a function of each specific analysis, given a common observational dataset. Surveys that cover large fractions of the sky, both well away from the ecliptic and to fainter limiting magnitudes, such as are planned for the forthcoming Large Synoptic Survey Telescope (LSST Science Collaboration et al. 2009), will discover many more such objects. However, archival data will clearly still yield new discoveries with further thorough searching.

For population studies, the detection efficiency of surveys such as PS1 need to be well characterized, as has been done

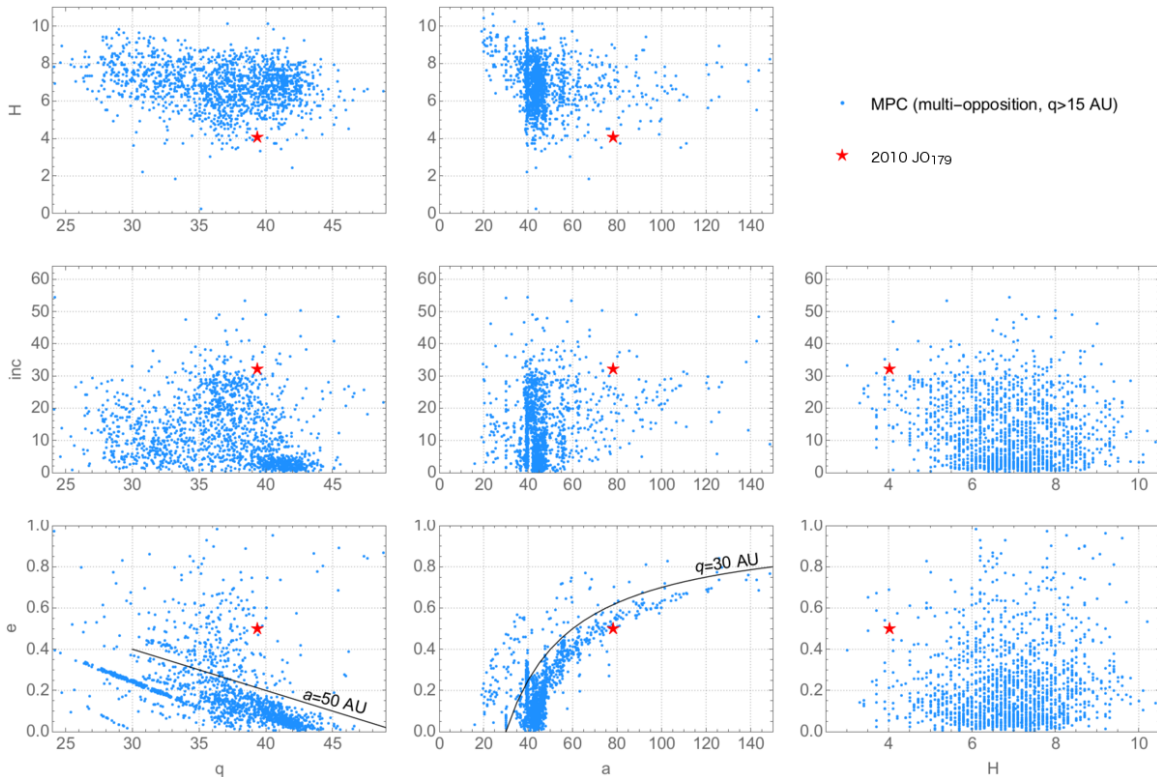


Figure 5. 2010 JO₁₇₉ placed in context among the other known TNOs.

for the CFEPS and OSSOS surveys (Petit et al. 2011; Bannister et al. 2016b), to be able to correct for the observational biases. In addition, detailed dynamical classifications of the discoveries, of the type we have done here, need to be made. These permit determination of the intrinsic abundance of TNOs such as 2010 JO₁₇₉ (e.g. Pike et al. 2015). This is the subject of future work with PS1.

With a perihelion distance $q = 39.32$ au (Fig. 5), near the boundary between what are considered to be low perihelion and high perihelion TNOs (Lykawka & Mukai 2007a; Gladman et al. 2008), 2010 JO₁₇₉ is a relatively nearby example of what is now being recognized as a very substantial population (Gomes 2003; Trujillo & Sheppard 2014; Pike et al. 2015; Kaib & Sheppard 2016; Nesvorný & Vokrouhlický 2016; Nesvorný et al. 2016). In the absence of a survey characterization, we cannot provide an absolute estimate for the 21:5 resonant population, especially given the strong observability bias on the eccentricity distribution of such a large- a population. However, we can find a general lower limit. The existence of 2010 JO₁₇₉ requires there to be at least one $H_r \simeq 3.5$ TNO. Scaling according to the size distribution of the dynamically excited TNOs (Fraser et al. 2014), there are at least 6700 objects in the 21:5 that are larger than 100 km in diameter. This would be more numerous than the 3:2 plutinos (Gladman et al. 2012), and is consistent with the large populations found in other distant resonances (Pike et al. 2015; Volk et al. 2016). Aspects of these large popula-

tions remain challenging to form in migration scenarios, cf. Pike et al. (2017a).

Neptune’s early migration into the outer planetesimal disk emplaced the dynamically excited trans-Neptunian populations, including the resonant and scattering disk (Malhotra 1995; Gomes 2003; Gladman et al. 2008). Predicting the details of the emplaced distant populations is an area of active investigation. Nesvorný et al. (2016) and Kaib & Sheppard (2016) independently predict that some TNOs with $a > 50$ au and $q > 40$ au should exhibit semi-major axes clustered near and inward, but not within, mean-motion resonances (MMR) with Neptune. This followed from modelling Neptune’s dynamical evolution on an orbit with moderate $e \lesssim 0.1$ eccentricity, both under smooth migration and from “grainy” gravitational interaction with a small sea of dwarf planets in the initial planetesimal disk (Nesvorný & Vokrouhlický 2016). In direct contrast, Pike & Lawler (2017) predict fairly symmetric trails of high-perihelia populations immediately surrounding distant mean-motion resonances. They assessed emplacement by the Nice model scenario of Brasser & Morbidelli (2013), with a smoothly migrating, initially high $e = 0.3$ Neptune. While one might hope to constrain the details of migration from the present-day orbit of a distant TNO like 2010 JO₁₇₉, it unfortunately lies in a region of phase space where its orbit does not distinguish among current model outcomes. Irrespective of whether Neptune’s migration was smooth or grainy, fast or slow, the results of

Nesvorný et al. (2016), Kaib & Sheppard (2016) and Pike & Lawler (2017) all contain TNOs with $a \sim 78$ au, $q \sim 39$ au, $i \sim 30^\circ$.

It is also worth considering if 2010 JO₁₇₉ could be a more recent arrival to its current orbit. The $a > 50$ au region is filigreed with high-order resonances. These permit “resonance sticking”, where a TNO’s orbit temporarily librates in resonance for tens to hundreds of millions of years, chaotically escapes the resonance, changing in semi-major axis, then sticks, librating within another resonance (e.g Lykawka & Mukai 2007b). The resonant dynamics during a temporary capture can lead to oscillations in eccentricity and inclination that can then weaken the TNO’s interaction with Neptune (Gomes et al. 2008; Sheppard et al. 2016). However, 2010 JO₁₇₉’s clones all remain close to its resonance (§ 5), implying stability for the age of the Solar System, rather than showing behaviour like that of 2015 RR₂₄₅, which moves between the 9:2 resonance and the scattering disk (Bannister et al. 2016a). 2010 JO₁₇₉’s clones exhibit similar behaviour to the four known TNOs in and by the 5:1 resonance at $a \sim 88$ au (Pike et al. 2015). The current orbit of 2010 JO₁₇₉ is therefore more likely to be ancient.

Facilities: PS1, NTT (EFOSC2), Sloan, CTIO:Blanco (DECam)

Software: Astropy, TRIPPy, REBOUND, Matplotlib

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APPENDIX

A. OBSERVATIONAL DATA

Table 3. Photometry of 2010 JO₁₇₉

Date (UTC)	Date (MJD)	Filter	m_{filter}	Exp (s)	Facility
2010-05-10 13:51:55.9	55326.577730	i	20.62 ± 0.10	45	PS1
2010-05-10 14:08:27.7	55326.589210	i	20.26 ± 0.10	45	PS1
2010-05-11 13:50:39.0	55327.576840	r	20.77 ± 0.09	40	PS1
2010-05-11 14:07:02.2	55327.588220	r	20.95 ± 0.11	40	PS1

Table 3 continued

Table 3 (continued)

Date (UTC)	Date (MJD)	Filter	m_{filter}	Exp (s)	Facility
2010-06-04 08:19:36.5	55351.346950	i	20.95 ± 0.09	45	PS1
2010-06-04 08:21:36.6	55351.348340	i	20.61 ± 0.07	45	PS1
2010-06-04 08:37:05.4	55351.359090	i	20.73 ± 0.08	45	PS1
2010-06-04 08:39:04.6	55351.360470	i	20.55 ± 0.07	45	PS1
2010-06-08 11:51:56.2	55355.494400	r	20.66 ± 0.09	40	PS1
2010-07-01 10:15:11.8	55378.427220	r	20.78 ± 0.10	40	PS1
2010-07-01 10:31:53.2	55378.438810	r	20.76 ± 0.09	40	PS1
2011-05-30 08:33:38.9	55711.356700	g	22.22 ± 0.21	43	PS1
2011-05-30 08:48:54.7	55711.367300	g	21.91 ± 0.15	43	PS1
2011-05-30 09:05:46.5	55711.379010	r	21.15 ± 0.08	40	PS1
2011-05-30 09:20:08.7	55711.388990	r	20.91 ± 0.07	40	PS1
2011-06-07 12:20:36.4	55719.514310	g	21.48 ± 0.13	43	PS1
2011-06-07 12:35:18.5	55719.524520	g	21.82 ± 0.16	43	PS1
2011-08-15 08:10:48.6	55788.340840	i	20.48 ± 0.21	45	PS1
2012-06-08 08:00:09.2	56086.333440	g	21.87 ± 0.20	43	PS1
2014-08-16 00:22:58.0	56885.015949	g	22.02 ± 0.09	84	DECam
2014-08-16 01:07:29.5	56885.046869	g	21.90 ± 0.09	88	DECam
2014-08-16 01:37:17.4	56885.067563	g	21.92 ± 0.10	82	DECam
2014-08-16 01:48:27.6	56885.075320	g	21.88 ± 0.09	87	DECam
2014-08-16 23:11:35.6	56885.966385	z	21.12 ± 0.24	122	DECam
2014-08-17 00:09:24.4	56886.006532	r	21.03 ± 0.07	70	DECam
2014-08-17 00:43:23.8	56886.030136	r	20.70 ± 0.10	72	DECam
2014-08-17 01:28:22.7	56886.061374	r	21.02 ± 0.11	69	DECam
2014-08-17 01:30:00.8	56886.062509	r	21.08 ± 0.10	71	DECam
2014-08-18 00:29:15.7	56887.020321	z	20.86 ± 0.09	121	DECam
2014-08-18 01:29:05.1	56887.061864	z	20.76 ± 0.10	124	DECam
2014-08-18 01:31:38.7	56887.063642	z	21.11 ± 0.13	127	DECam
2016-07-28 02:51:47.5	57597.119300	r	21.18 ± 0.03	300	NTT
2016-07-28 02:57:24.5	57597.123200	r	21.15 ± 0.04	300	NTT
2016-07-28 03:03:01.4	57597.127100	r	21.22 ± 0.05	300	NTT
2016-07-28 03:08:55.7	57597.131200	r	21.13 ± 0.07	300	NTT
2016-07-28 03:14:32.6	57597.135100	g	22.08 ± 0.12	300	NTT
2016-07-29 23:24:08.6	57598.975100	r	21.27 ± 0.03	300	NTT
2016-07-29 23:29:37.0	57598.978900	r	21.29 ± 0.03	300	NTT
2016-07-29 23:35:13.9	57598.982800	r	21.30 ± 0.03	300	NTT
2016-07-30 00:20:26.9	57599.014200	r	21.25 ± 0.02	300	NTT
2016-07-30 00:26:12.5	57599.018200	g	22.09 ± 0.03	300	NTT
2016-07-30 00:31:58.1	57599.022200	r	21.22 ± 0.03	300	NTT

Table 3 continued

Table 3 (*continued*)

Date (UTC)	Date (MJD)	Filter	m_{filter}	Exp (s)	Facility
2016-07-30 00:54:08.6	57599.037600	r	21.30 ± 0.03	300	NTT
2016-07-30 00:59:54.2	57599.041600	g	21.99 ± 0.04	300	NTT
2016-07-30 01:05:31.2	57599.045500	r	21.20 ± 0.03	300	NTT
2016-07-30 01:31:35.0	57599.063600	r	21.19 ± 0.02	300	NTT
2016-07-30 01:36:11.5	57599.066800	r	21.18 ± 0.03	300	NTT
2016-07-30 01:58:39.4	57599.082400	r	21.17 ± 0.02	300	NTT
2016-07-30 02:04:25.0	57599.086400	g	21.95 ± 0.03	300	NTT
2016-07-30 02:10:10.6	57599.090400	r	21.17 ± 0.02	300	NTT
2016-07-30 02:33:04.3	57599.106300	r	21.15 ± 0.03	300	NTT
2016-07-30 02:37:40.8	57599.109500	r	21.14 ± 0.02	300	NTT
2016-07-30 03:16:59.5	57599.136800	r	21.15 ± 0.02	300	NTT
2016-07-30 03:21:36.0	57599.140000	r	21.09 ± 0.02	300	NTT

NOTE—PS1 and DECam photometry measured with TRIPPy (Fraser et al. 2016), NTT photometry measured with circular aperture photometry.

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