A New High Perihelion Trans-Plutonian Inner Oort Cloud Object: 2015 TG387

Scott S. Sheppard1, Chadwick A. Trujillo2, David J. Tholen3, and Nathan Kaib4

1 Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Road NW, Washington, DC 20015, USA
2 ssheppard@carnegiescience.edu
3 Northern Arizona University, Flagstaff, AZ 86011, USA
4 Institute for Astronomy, University of Hawai‘i, Honolulu, HI 96822, USA

Received 2018 September 5; revised 2019 February 7; accepted 2019 February 18; published 2019 March 12

Abstract

Inner Oort cloud objects (IOCs) are trans-Plutonian for their entire orbits. They are beyond the strong gravitational influences of the known planets, yet close enough to the Sun that outside forces are minimal. Here we report the discovery of the third known IOC after Sedna and 2012 VP113, called 2015 TG387. This object has a perihelion of 65 ± 1 au and semimajor axis of 1170 ± 70 au. The longitude of perihelion angle, ω, for 2015 TG387 is between that of Sedna and 2012 VP113 and thus similar to the main group of clustered extreme trans-Neptunian objects (ETNOs), which may be shepherded into similar orbital angles by an unknown massive distant planet called Planet X, or Planet Nine. The orbit of 2015 TG387 is stable over the age of the solar system from the known planets and Galatic tide. When including outside stellar encounters over 4 Gyr, 2015 TG387’s orbit is usually stable, but its dynamical evolution depends on the stellar encounter scenarios used. Surprisingly, when including a massive Planet X beyond a few hundred au on an eccentric orbit that is antialigned in longitude of perihelion with most of the known ETNOs, we find that 2015 TG387 is typically stable for Planet X orbits that render the other ETNOs stable as well. Notably, 2015 TG387’s argument of perihelion is constrained, and its longitude of perihelion librates about 180° from Planet X’s longitude of perihelion, keeping 2015 TG387 antialigned with Planet X over the age of the solar system.

Key words: comets: general – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: individual (2015 TG387)

Supporting material: machine-readable table

1. Introduction

Extreme trans-Neptunian objects (ETNOs) have perihelia well beyond Neptune and large semimajor axes (\( a > 150–250 \) au). The ETNOs have only minimal interactions with the known giant planets and thus are strongly sensitive to gravitational forces hundreds to thousands of au from the Sun. Thus, the ETNOs can be used to probe the solar system beyond the Kuiper Belt (Trujillo & Sheppard 2014).

The ETNOs can be separated into three subclasses (Figure 1). The scattered ETNOs have perihelia below \( 38–45 \) au and likely were created from gravitational scattering with Neptune and still have strong to moderate interactions with the known giant planets (Brasser & Schwamb 2015). The detached ETNOs have more distant perihelia of between about 40–45 and 50–60 au but could still have significant interactions with the known giant planets (Gladman et al. 2002; Bannister et al. 2017). Inner Oort cloud objects (IOCs) or trans-Plutonian objects have perihelia greater than 50–60 au and are too far from the giant planets to be strongly influenced by them (Gomes et al. 2008). The origins of the eccentric IOC orbits likely required mechanisms that operated more efficiently in the past, such as stronger outside stellar tide forces or uncataloged forces in the outer solar system (Fernandez 1997; Brown et al. 2004; Kenyon & Bromley 2004; Madigan et al. 2018; Setfilian & Touma 2019). The orbits of the IOCs thus inform us how the distant solar system formed and currently interacts with its surroundings. The detached ETNOs may have evolved in a similar manner as the IOCs or could be more similar to the scattered ETNOs. Any object with an aphelion beyond a few thousand au is considered an outer Oort cloud object, as outside forces such as the Galactic tide and passing stars become strongly significant at these distances (Kaib et al. 2009).

Sedna’s large semimajor axis means that past stronger stellar tidal forces experienced by the solar system in the Sun’s birth cluster would likely create Sedna’s detached orbit, making this the preferred formation mechanism of IOCs (Kaib & Quinn 2008; Brasser et al. 2012). The much smaller semimajor axis of 2012 VP113 and its even higher perihelion compared to Sedna means that it is harder for the stellar cluster tidal formation scenario to work in creating 2012 VP113’s detached orbit (Trujillo & Sheppard 2014).

Trujillo & Sheppard (2014) noticed that the ETNOs appear to have orbital clustering in their argument of perihelion and were possibly asymmetric in longitude; they suggested that there is a super-Earth or larger-mass planet beyond a few hundred au shepherding these objects into similar types of orbits. Batygin & Brown (2016a) determined a possible orbit a planet could have to cause the ETNOs to be aligned, with the planet orbit needing to be eccentric, inclined, and at several hundred au. After the above works, there have been several more in-depth analyses of the ETNOs and how they would evolve and interact under such a massive planet in the outer solar system (Batygin & Morbidelli 2017; Iorio 2017; Nesvorny et al. 2017; Shankman et al. 2017a; Hadden et al. 2018; Khain et al. 2018; Li et al. 2018). High-inclination trans-Neptunian objects could be created by the planet (Batygin & Brown 2016b). The planet should also cause resonant behavior in the ETNOs (Malhotra et al. 2016; Millholland & Laughlin 2017; Bailey et al. 2018), though the ETNOs may jump between various orbital resonances and configurations.
(Becker et al. 2017). One of the most interesting behaviors of the ETNOs is the libration of the longitude of perihelion with that of the unknown planet, which was seen in numerical simulations of the ETNO 2013 FT28 by Sheppard & Trujillo (2016). This object was announced after the possible planet orbital parameters were reported by Batygin & Brown (2016a), so it makes the case stronger that the massive unknown planet beyond a few hundred au exists.

Here we detail the discovery of only the third object with a known perihelion beyond 60 au, 2015 TG387, and how its orbit compares to the other known IOCs and ETNOs. We then discuss the stability of 2015 TG387 through numerical simulations we performed involving the known major planets, Galactic tide, stellar passages, and a possible massive Planet X beyond a few hundred au.

2. Basic Survey and Observation Details

We discovered 2015 TG387 in our ongoing survey for objects beyond the Kuiper Belt edge. This survey is discussed in detail in Trujillo & Sheppard (2014) and Sheppard & Trujillo (2016), where several ETNOs were discovered, including 2012 VP113, 2014 SR349, and 2013 FT28. Here we report additional fields from the survey (Table 1) and discuss the discovery and implications of 2015 TG387 within these fields. A more detailed paper on the full survey and the discoveries made will follow later.

Table 1

| UT Date       | Telescope | $T$ (hr) | $\theta$ (arcsec) | Limit (m) | Area (deg$^2$) |
|---------------|-----------|----------|-------------------|-----------|----------------|
| yyyy/mm/dd    | Subaru    |          |                   |           |                |
| 2015 Mar 17   | hsc0440   | 10:51:19 | +11:36:00         |           |                |
|               | hsc0372   | 10:38:07 | +07:48:00         |           |                |
|               | hsc0406   | 10:44:19 | +10:57:00         |           |                |
|               | hsc0429   | 10:49:07 | +09:24:00         |           |                |
|               | hsc0460   | 10:55:19 | +10:12:00         |           |                |
|               | hsc0494   | 11:02:07 | +10:45:00         |           |                |
|               | hsc0534   | 11:09:55 | +10:00:00         |           |                |
|               | hsc0607   | 11:22:43 | +09:27:00         |           |                |
|               | hsc0660   | 11:33:31 | +09:18:00         |           |                |
|               | hsc0724   | 11:45:31 | +09:27:00         |           |                |
|               | hsc0741   | 11:49:31 | +07:12:00         |           |                |
|               | hsc0779   | 11:56:31 | +07:21:00         |           |                |
|               | hsc0823   | 12:04:19 | +05:54:00         |           |                |
|               | hsc0871   | 12:12:31 | +04:51:00         |           |                |
|               | hsc0901   | 12:18:19 | +05:51:00         |           |                |
|               | hsc1107   | 12:57:07 | +04:27:00         |           |                |
|               | hsc1129   | 13:00:55 | +03:00:00         |           |                |
|               | hsc1160   | 13:06:55 | +03:51:00         |           |                |
|               | hsc1178   | 13:10:31 | +02:24:00         |           |                |
|               | hsc1193   | 13:12:43 | +04:45:00         |           |                |
|               | hsc1210   | 13:17:07 | +02:12:00         |           |                |
|               | hsc1249   | 13:23:07 | +04:03:00         |           |                |
|               | hsc1283   | 13:29:07 | +04:54:00         |           |                |
|               | hsc1259   | 13:25:19 | +07:33:00         |           |                |

Note. The instruments used were the HSC on Subaru, DECam on the CTIO 4 m, the LB Camera on the Large Binocular Telescope, and IMACS on Magellan. These are fields in our survey in addition to the fields presented and detailed in Sheppard & Trujillo (2016). Here $T$ is the approximate amount of time between the first and last images of a field, $\theta$ is the range of seeing for the night, and Limit is the limiting magnitude in the $r$ band where we would have found at least 50% of the slow-moving objects in most of the fields. Under the basic survey information for each night are the fields observed in J2000 coordinates for R.A. (hh:mm:ss) and decl. (dd:mm:ss). Field names are the names used at the telescope for each field and likely to be unimportant, but they are included for full information.

For discovery, our survey mainly uses the 8.2 m Subaru telescope (atop Maunakea, Hawaii) in the Northern Hemisphere with the 1.5 deg$^2$ Hyper Suprime-Cam (HSC) and the 4 m Blanco telescope (at Cerro Tololo Inter-American Observatory) in the Southern Hemisphere with the 2.7 deg$^2$ Dark Energy Camera (DECam; Flaugher et al. 2015). Any objects found beyond about 50 au are recovered months and years later with the 6.5 m Magellan and 4 m Discovery Channel Telescope (DCT) to obtain the orbits of the objects. The $r$-band Subaru HSC images generally have exposure times of about 300 s, but exposure times are increased or decreased in order to reach about 25.5 mag in the $r$ band, depending on the observing conditions for each night. The DECam images use a very wide broadband VR filter and are generally 420 s, with exposure times varied depending on the observing conditions to reach near 25th magnitude in the $r$ band. The field depths, time base, and coordinates of the fields are shown in Table 1. Figure 2 shows the field locations on the sky. Table 1 has about 1050 deg$^2$ of new fields, giving the total surveyed area to date about 2130 deg$^2$ when including the fields from Sheppard & Trujillo (2016).
3. Discovery and Orbit of 2015 TG387

On UT 2015 October 13, 2015 TG387 was found near 80 au at Subaru with a magnitude of 24.0 in the r band. Surprisingly, like 2012 VP113, 2015 TG387 is relatively bright compared to the limiting magnitude of most of the survey fields. The Subaru observations generally go deeper than 25.5 mag, making 2015 TG387 about 1.5 mag brighter than the limiting magnitude of the discovery survey fields it was found in. At 80 au, the expected diameter of 2015 TG387 would be about 300 km, assuming a moderate albedo of 15%.

The object 2015 TG387 was recovered in 2015 December; 2016 September, October, November, and December; 2017 September and December; and 2018 May. It thus has multiple observations during four separate oppositions. The barycentric orbital elements and their current uncertainties are shown in Table 2. The object has a moderately reliable orbit. Because the semimajor axis has been found to be one of the largest known for a trans-Neptunian object that always stays beyond Neptune, second only to 2014 FE72 (Sheppard & Trujillo 2016), the uncertainties in the orbit of 2015 TG387 are still modest, even with the multiple oppositions of observations. We find a semimajor axis of $a = 1170 \pm 70$ au, eccentricity of $e = 0.945 \pm 0.003$, inclination of $i = 11^\circ \pm 5001$, longitude of the ascending node of $\Omega = 300^\circ 98 \pm 0^\circ 01$, and argument of perihelion of $\omega = 118^\circ 2 \pm 0^\circ 1$ at an epoch of 2457308.8. This makes the argument of perihelion closer to 180° than 0°, which is unlike Sedna, 2012 VP113, and most of the other ETNOs, as discussed in Trujillo & Sheppard (2014). In fact, 2015 TG387 is the first detached ETNO or IOC to have an argument of perihelion closer to 180° as opposed to 0° (Figure 3), but as discussed below, Planet X can constrain the argument of perihelion of 2015 TG387 to be near 0°, like that found for the other ETNOs and IOCs.

3.1. Longitude of Perihelion of 2015 TG387

The longitude of perihelion of 2015 TG387 is $\omega = \omega + \Omega = 59^\circ 2 \pm 0^\circ 2$. Trujillo & Sheppard (2014) suggested that the IOCs might be asymmetric in longitude, but they believed that there were significant observational biases in the longitude discoveries of these objects, and thus any longitude asymmetries would require further unbiased extreme object discoveries. Batygin & Brown (2016a), using the biased longitudinal observational results of ETNOs, suggested that the longitudes of perihelion of many of the ETNOs are clustered between about 0° and 120°. Sheppard & Trujillo (2016) further examined the longitude of perihelion similarities after discovering more ETNOs in a low biased longitudinal survey. Sheppard & Trujillo (2016) concluded that the asymmetry in longitude for the ETNOs is likely real but still marginal at about the 3σ level with the additional discoveries reported in the 2016 paper and assuming all known ETNOs have observational biases similar to their own survey. Additional analysis by Brown (2017) using all of the ETNOs with their observational biases further finds the clustering likely real. Shankman et al. (2017b) did not find an obvious longitude of perihelion clustering for ETNOs, though their analysis used a limited set of surveyed longitudes and a liberal definition of what is an ETNO. The Shankman et al. (2017b) results are hindered by a lack of uniform sky coverage and low number statistics, making their results hard to interpret. This is the reason we are performing a very uniform and extensive survey.

Our survey has now covered even more sky since Sheppard & Trujillo (2016), and our longitude biases are now even smaller. The object 2015 TG387 was found about 45° away in R.A. on the sky from Sedna and 2012 VP113; in addition, unlike Sedna and 2012 VP113, it was not found within a few au of perihelion but about 15 au away from perihelion at around 80 au. It is brighter than 25.5 mag over an R.A. range of about 23–9 hr, which corresponds to heliocentric distances less than about 100 au, after which 2015 TG387 would be too faint for us to efficiently discover. This means that 2015 TG387 could easily have been discovered and/or had a longitude of perihelion well away from the other two known IOCs, but the longitude of perihelion is between Sedna and 2012 VP113. Thus, 2015 TG387 continues the longitude clustering trend seen for the IOCs and ETNOs, which might be caused by a massive planet shepherding these objects (Figure 4).

3.2. Inner Oort Cloud Observational Simulation: Longitude of Perihelion

Sedna, 2013 VP113, and 2015 TG387 all have similar longitudes of perihelion (96°, 25°, and 59°, respectively). These are the only objects known with perihelia greater than 60 au, where Neptune’s gravitational effects are mostly insignificant (Gomes et al. 2008; Brasser & Schwamb 2015). Both 2013 VP113 and 2015 TG387 were discovered in our survey, which attempts to have low biases in longitude discovery by observing at all times of the year. We can simulate their detection statistics and biases using methods similar to those of Sheppard & Trujillo (2016). Sedna is bright enough that almost the whole sky has been searched for such bright objects; thus, Sedna can be considered to have no discovery bias in longitude (Brown 2008; Sheppard et al. 2011; Rabinowitz et al. 2012). The observed longitude of perihelion distribution given to Sedna, 2015 TG387, and 2013 VP113 is $\omega = 60^\circ \pm 35^\circ$, which is a fairly narrow standard deviation. Assessing whether this observation is consistent with a uniform distribution is not straightforward, given the small number of detections and the fact that $\omega$ is a continuous angle across the sky. Kuiper’s one-sided variation of the Kolmogorov–Smirnov statistic might normally be used, but its statistics are not well defined for a number of detections less than four.
Above are the orbits of the IOCs and ETNOs discovered in our survey. Quantities are the perihelion longitude of the ascending node ($\Omega$), argument of perihelion ($\omega$), longitude of perihelion ($\varpi$), semimajor axis ($a$), inclination ($i$), and distance at discovery ($b$). Elements for Sedna and 2012 VP113 are taken from JPL Horizons and truncated to three significant digits.

| Name | $q$ (au) | $a$ (au) | $e$ | $i$ (deg) | $\Omega$ (deg) | $\omega$ (deg) | $\varpi$ (deg) | $b$ (deg) | Dist. (au) | Dia. (km) | Dia. (mag) |
|------|---------|---------|-----|---------|-------------|-------------|-------------|---------|---------|---------|-----------|
| This Survey Inner Oort Cloud Discoveries | | | | | | | | | | | |
| 2015 TG387 | 65 ± 1 | 1170 ± 70 | 0.945 | 11.670 | 300.98 | 118.2 | 59.2 | 10.7 | 80.0 | 300 | 24.0 |
| 2012 VP113 | 80.569 | 270.495 | 0.702 | 24.016 | 90.886 | 294.138 | 25.024 | 16.637 | 82.873 | 450 | 23.22 |
| Other Unbiased IOCs | | | | | | | | | | | |
| Sedna | 76.167 | 540.623 | 0.859 | 11.928 | 144.502 | 311.106 | 95.608 | 11.855 | 89.593 | 1000 | 21.04 |
| This Survey Detached ETNOs Conservative Definition ($q > 45$ au) | | | | | | | | | | | |
| 2014 SR349 | 47.483 | 290.845 | 0.836 | 17.974 | 34.839 | 341.533 | 16.372 | 17.1 | 57.2 | 200 | 24.1 |
| This Survey Detached ETNOs Liberal Definition ($q > 40$ au) | | | | | | | | | | | |
| 2013 FT28 | 43.586 | 295.912 | 0.852 | 17.381 | 217.710 | 40.430 | 101.860 | 7.0 | 58.9 | 200 | 24.2 |

**Note.** Above are the orbits of the IOCs and ETNOs discovered in our survey. Quantities are the perihelion ($q$), semimajor axis ($a$), eccentricity ($e$), inclination ($i$), longitude of the ascending node ($\Omega$), argument of perihelion ($\omega$), longitude of perihelion ($\varpi$), ecliptic latitude at discovery ($\bar{b}$), and distance at discovery (Dist.). Diameter (Dia.) estimates assume a moderate albedo of 0.15. Uncertainties for 2015 TG387, if not shown explicitly, are shown by the number of significant digits. Elements for Sedna and 2012 VP113 are taken from JPL Horizons and truncated to three significant digits.

Figure 3. Semimajor axis vs. argument of perihelion for all objects with perihelia greater than 40 au. The colors are the same as described in Figure 1. There is a noticeable clustering between 290° and 40°, of which 2015 TG387 is the first detached ETNO or IOC to be closer to 180° than 0° with a semimajor axis beyond 250 au.

(Press et al. 1992), nor is it particularly sensitive with such a low number of detections.

To determine if the longitude of perihelion trend is statistically significant, we first examine a simplistic case, where we consider Sedna’s longitude of perihelion as an a priori value, then draw two objects (2015 TG387 and 2013 VP113) from a uniform distribution in $\varpi$, ignoring observational biases. If both objects were within 35° of Sedna’s $\varpi$, then the standard deviation of all three objects would be less than 35°. Assuming binomial statistics, this would happen with a probability of $P = \left(\frac{2 \times 35°}{360°}\right)^2 = 0.038$, or the equivalent of 2.1σ, assuming Gaussian statistics. This method uses only the three known IOCs and does not take observational biases into account.

To simulate observational biases more thoroughly, we assume that 2015 TG387 and 2013 VP113 are drawn from the same population of extremely distant objects. We use the distribution detailed in Table 3 as the underlying distribution, assuming that the objects have a uniform longitude and argument of perihelion. We then tally the number of objects in our observational simulation that would be detected given our combination of survey field sky locations and depths. The resulting survey longitude of perihelion bias is shown in Figure 5. We then assess whether the distribution of $\varpi$ for the simulated detections is consistent with the actual observed distribution of $\varpi = 60° \pm 35°$. For this, we require that a randomly selected group of two simulated detected objects, together with Sedna, have a standard deviation of less than 35° and that the mean also differ from 60° by less than 35°. We constructed a simple Monte Carlo simulation and found that these criteria are satisfied about 5% of the time by a uniform distribution, or about a 2σ significance that the IOCs are not drawn from a uniformly distributed population in longitude of perihelion. As seen in Figure 5 and the results above, our survey has fairly uniform longitude of perihelion discovery statistics, as including our observational biases only slightly changes the probability, making an asymmetric population of IOCs a little less significant.

The results in the previous paragraph are for $q = 4$ power-law size distribution. We also simulated a $q = 5$ power-law size distribution and found similar results. We conclude that although the longitude of perihelion clustering continues to appear intriguing, with only three known IOCs, several more need to be discovered in low-bias longitude surveys for this effect to be statistically significant at the 3σ level for IOCs.

3.3. ETNO Observational Simulation: Longitude of Perihelion

We now include the discovery statistics of the detached ETNOs along with the IOCs from our survey. The detached ETNOs can be observationally differentiated from the IOCs because of their more moderate perihelia (40–45 au < $q < 50–60$ au) compared to the IOCs’ extremely high perihelia of $q > 50–60$ au. The detached ETNOs may have similar formation and evolutionary histories as the IOCs, but they are significantly closer to the giant planets and thus could have obtained their orbits through different processes (Brasser & Schwamb 2015; Bannister et al., 2017). Assuming a $q > 40–45$ au and $a > 150–250$ au definition for the detached ETNOs, the detached ETNOs found in our survey are safely 2014 SR349 and, if less conservative, also 2013 FT28 (Table 2). We also found several ETNOs that have lower
perihelia than 40 au and thus are not detached but scattered ETNOs with more interactions with Neptune: 2014 FE72, 2013 UH15, 2013 FS28, and 2014 SS349. These scattered ETNOs were detailed in Sheppard & Trujillo (2016); here we only consider the detached ETNOs 2014 SR349 and 2013 FT28, and in the most conservative case, we only consider 2014 SR349, with its perihelion above 45 au and semimajor axis above 250 au.

The statistics for the longitude of perihelion in our survey fields for the IOCs if drawn from a uniform longitude of perihelion distribution using the parameters shown in Table 3. The ecliptic longitudes within 15° of where the Galactic plane crosses the ecliptic are shaded in gray (southern decl. is left, and northern decl. is right). The fact that the highest and lowest points differ by only about a factor of 2 in all but a few cases suggests that our survey has fairly low observational biases for longitude of perihelion. The longitudes of perihelion of Sedna, 2012 VP113, and 2015 TG387 are shown by filled circles, while their locations at discovery are shown by open circles.

Figure 4. Plan view of the IOCs (q > 60 au; Sedna and 2012 VP113 in purple), detached ETNOs (most conservative definition in blue with 45 au < q < 50 au and a > 250 au: 2015 RX245, 2014 SR349, 2013 SY99, 2010 GB174, and 2004 VN112; less conservative definition in black with 40 au < q < 45 au and a > 150 au: 2015 KG163, 2013 UT15, 2013 GP136, 2013 FT28, and 2000 CR105), and the newly discovered IOC 2015 TG387 (red). All but the least conservative detached ETNOs are antialigned in longitude of perihelion with a possible distant planet on an eccentric orbit (green). There is a second grouping of ETNOs that, to date, generally have lower perihelia and appear aligned with the planet in longitude of perihelion.

Table 3

| Parameter          | Value | Description                                      |
|--------------------|-------|--------------------------------------------------|
| $R_{min}$          | 50 au | Minimum heliocentric distance detectable in survey|
| $R_{max}$          | 500 au| Maximum heliocentric distance detectable in survey|
| $\rho$             | 1000 kg m$^{-3}$ | Density                                      |
| $p_r$              | 0.15  | Albedo in r filter                                |
| $r_{min}$          | 20 km | Minimum radius                                    |
| $r_{max}$          | 1200 km| Maximum radius                                    |
| $e_{min}$          | 0.65  | Minimum eccentricity                              |
| $q'$               | 4     | Size distribution power-law exponent             |
| $\sigma_i$         | 6°/9  | $\sigma$ for Gaussian inclination distribution   |
| $\mu_i$            | 19°1  | Mean for Gaussian inclination distribution       |
| $q_{min}$          | 50 au | Minimum perihelion                               |
| $q_{max}$          | 500 au| Maximum perihelion distance                      |
| $N_{obs}$          | 2     | Number of observed objects: 2012 VP113 and v302126|

| Conservative ETNO + IOC Simulation: Same as IOC Simulation Except |
|--------------------|-------|--------------------------------------------------|
| $q_{min}$          | 45 au | Minimum perihelion                               |
| $N_{obs}$          | 3     | Number of observed objects: 2012 VP113, v302126, 2014 SR349 |

Notes. Observational bias simulation parameters for both the IOC and ETNO + IOC combined simulation. We also ran simulations with both q = 5 and a = 1, as described in the text.

The Astronomical Journal, 157:139 (14pp), 2019 April Sheppard et al.
Sedna drawn from a uniform distribution in \( \omega \) and ignoring observational bias. Only 1.5% of the time do these three objects have \( \omega \) close enough to Sedna for the mean of all objects to be within \( 49^\circ \pm 36^\circ \) and the standard deviation to be \( <36^\circ \), the equivalent of a 2.4\( \sigma \) event in Gaussian statistics. Using our observational bias simulator and the method in Section 3.2, we find that these criteria are met only \( P = 2.8\% \) of the time when the ETNOs and IOCs are drawn from a uniform \( \omega \) distribution. This is the equivalent of 2.2\( \sigma \) in the Gaussian case, which again is interesting but not statistically significant at the 3\( \sigma \) level, since only four objects are used in the analysis.

Using the more liberal definition in perihelion of a detached ETNO of \( q > 40 \) au and \( a > 250 \) au would cause 2013 FT28 to be included in the detached ETNO group as well. The orbit of 2013 FT28 has \( \omega = -101^{\circ}.860 \), which departs from the mean of the other IOCs and ETNOs by about 180\( ^\circ \). Sheppard & Trujillo (2016) proposed that 2013 FT28 is the first known ETNO aligned with Planet X in longitude of perihelion. A distant massive planet on an elongated orbit would likely create both an antialigned and aligned longitude of perihelion population of ETNOs with respect to the planet’s longitude of perihelion (Brown & Batygin 2016). That is, the aligned population has a longitude of perihelion similar to that of the hypothesized planet on an elongated orbit, while an antialigned population would differ by about 180\( ^\circ \).

If we make the assumption that 2013 FT28 is a member of the opposite ETNO population from Sedna, 2012 VP112, 2015 TG387, and 2014 SR349, its longitude of perihelion does indeed fit the \( \omega \) pattern already discussed as 180\( ^\circ \). This was the case, this would decrease the probability that \( \omega \) for the ETNOs and IOCs was drawn from a random uniform distribution. From our observational bias simulation, this would suggest \( P = 0.013 \), or 2.5\( \sigma \) in Gaussian statistics. Again, this is not yet statistically significant, as there are only a few objects used, but it is cause for interest.

Above, we are trying to use only objects found in low-bias longitude surveys, but very few objects have been found like this, which is the main reason we are continuing our survey. Taking all known conservatively defined detached ETNOs and IOCs \((q > 45 \) au and \( a > 250 \) au) into account finds eight objects (Sedna, 2012 VP112, 2015 TG387, 2014 SR349, 2004 VN112, 2010 GB174, 2013 SY99, 2014 RX245), all with longitudes of perihelion between 15\( ^\circ \) and 120\( ^\circ \). This has a 0.005% chance of happening and is about a 4\( \sigma \) event, if ignoring possible observational biases.

We note that the above methods include a priori assumptions identifying the location of the longitude of perihelion clustering, as well as the specific choices of objects and the population membership of 2013 FT28. We additionally measured the statistical significance of the eight longitude of perihelion measurements using the R package CircStats (Jammalamadaka & SenSupta 2001) implementation of the Kuiper test for circularly distributed variables (result 2.2 with probability drawn from uniform distribution \(<1\%\), as well as the Rayleigh test for uniformity (result mean length 0.84 with probability drawn from uniform distribution 0.16\%, equivalent of 3.2\( \sigma \) assuming Gaussian statistics). These tests are a little lower in significance than the binomial test. They have the advantage that they do not presuppose a specific longitude of perihelion range but the disadvantage that they are best suited for larger data sets. So again, the longitude of perihelion clustering is interesting, but further low biased discoveries are needed to make it statistically significant.

3.4. The Inner Oort Cloud Semimajor Axis Distribution

We have detected two IOCs in our survey with very different semimajor axes. 2015 TG387 with \( a = 1170 \) au and 2012 VP113 with \( a = 270 \) au. This suggests a semimajor axis distribution that has more distant objects than the \( a^1 \) assumed by Sheppard & Trujillo (2016), a value that was largely assumed due to limited discovery statistics. Since solar system volume increases with heliocentric distance as \( R^2 \), although an \( a^1 \) semimajor axis distribution has more objects with large semimajor axes than small, the real underlying space density of objects for an \( a^2 \) distribution would fall as \( R^{-2} \). According to our observational bias simulations, assuming \( a^3 \), one would expect to find about 23 objects within 10 au of 2012 VP113’s low semimajor axis for every object within 10 au of 2015 TG387’s high semimajor axis. Since the number of true detections is only two, we cannot statistically rule out the possibility of an \( a^1 \) semimajor axis distribution. However, we find that to observe equal numbers of \( a = 270 \) and 1170 au objects, we would have to draw them from an \( \sim a^{2.7} \) semimajor axis distribution. Such a semimajor axis distribution would imply a much larger number of IOCs and a population that is highly dependent on the number of very distant objects, which are the most difficult to observe. All other parameters remaining the same, this \( a^{2.7} \) population would have to be a factor of \( \sim 2 \) larger than an \( a^1 \) population. We use this \( a^{2.7} \) semimajor axis distribution as our favored semimajor axis distribution for the remainder of this work. Interestingly, if the true semimajor axis distribution is close to a power law of exponent 3, as these simulations suggest, this implies a fairly constant space density of objects moving outward with distance.

3.5. Population Number and Mass of IOCs

From the observational simulations, we find that the total number of IOCs is quite large, mainly because IOCs can only be detected for a small fraction of their orbits. For 2015 TG387, assuming a semimajor axis of 1170 au and a perihelion of 65 au, 2015 TG387 will be fainter than our faintest HSC survey field depths, \( r \sim 25.5 \) mag, for 99.5% of its orbital period. Using our observational bias simulation with a variety of parameters (combinations of \( q = 4, 5 \) and \( a = 2.7 \)), the total number of objects larger than radius 20 km based on our two detections (2015 TG387 and 2012 VP113) is roughly \( 2 \times 10^6 \), with a total mass of about \( 10^{22} \) kg. This total mass likely exceeds that of classical dynamically “cold” TNOs and is similar to the dynamically “hot” TNOs, which have masses of about \( M = 1.8 \times 10^{21} \) and \( 6.0 \times 10^{22} \) kg, respectively (Fraser et al. 2014). This is a lower limit on the IOC mass, given that we have almost no constraints on distant, low-eccentricity objects that are unobservable given current technology. Sheppard & Trujillo (2016) showed that the cumulative luminosity function and size distribution of the ETNOs and IOCs are likely similar to the Kuiper Belt as well.

3.6. Observational Bias Simulation: Inclination Distribution

The inclinations of our IOCs and detached ETNOs are moderate, in the range \( 11^{\circ}\text{.7} < i < 24^{\circ}\text{.0} \). Our survey observed
mostly between 5° and 25° from the ecliptic, though we did approach the ecliptic and thus were sensitive to objects with inclinations significantly lower than that detected. We can say that the inclination distribution of the IOCs and detached ETNOs is quite thick, and in fact, in our survey simulation, we found by Gulbis et al. (2010; \( \mu_1 = 19.1 \) and \( \sigma_1 = 6.9 \)), as this is similar to the average ETNO inclination found by Sheppard & Trujillo (2016). Our observational bias simulator suggests that the observed ETNO/IOC inclination distribution is consistent with the inclination distribution of the scattered disk objects.

We can rule out narrow distributions for the ETNOs/IOCs. For instance, our observations are not consistent with the more inclined component of the classical Kuiper belt objects (KBOs; \( \sigma_3 = 8.1 \); Gulbis et al. 2010). The simulated detected distribution in this case has a mean inclination of \( i = 10.5 \pm 4.8 \). This is inconsistent with the detection of 2012 VP113 with an inclination of \( i \sim 24° \). From our observational bias simulation, the probability of us discovering an object with \( i > 24° \) is 0.0032, which is ruled out at the 3\( \sigma \) level assuming Gaussian statistics. Given this and the fact that 2013 FT28 and 2014 SR349 have inclinations \( i > 17 \) that each have a probability of discovery of only 0.22, we can reject the hypothesis that the ETNOs/IOCs follow the inclination distribution of the classical TNO populations at the >3\( \sigma \) level.

We can also say that the IOCs and detached ETNOs likely do not have a high-inclination distribution like that found for TNOs with perihelion above 40 au and experiencing both Neptune mean-motion resonance (MMR) and Kozai resonance (KR) behavior. These MMR-KR objects have an average \( i \sim 28° \) (Sheppard et al. 2016), and we have found no detached ETNOs or IOCs with inclinations this high while finding several even more inclined MMR-KR objects in the same survey. One very high inclination scattered ETNO has been found, 2015 BP519, with an inclination of 54°, but this object has a fairly low perihelion near Neptune and thus may not be related to the IOCs and detached ETNOs with much higher perihelias (Becker et al. 2018).

### 3.6.1. Inner Edge of the Inner Oort Cloud

We do not know whether the trans-Plutonian IOCs (\( q > 50–60 \) au) and the ETNOs (\( q < 50–60 \) au) have similar origins or could be formed from different mechanisms. The ETNOs have low enough perihelion that their orbits can still be modified by interactions with the known giant planets. The object 2015 TG387 has such a large orbit that outside forces can have significant effects on its orbit (see below); thus, its orbit can also be modified, but likely in a different manner than the ETNOs. To date, 2012 VP113 and Sedna are the only known objects with high enough perihelion and low enough aphelion that their orbits are not significantly modified by any known forces, either internal (the giant planets) or external (the galactic tide and passing stars). Trujillo & Sheppard (2014) suggested an inner edge to the IOC population, and Sheppard & Trujillo (2016) expanded on this, since no IOCs or ETNOs have been discovered with perihelion between about 50 and 75 au, though they would be significantly easier to discover than the more distant Sedna and 2012 VP113.

Some simulations of stellar encounters (Morbidelli & Levison 2004) suggest that an inner edge to the IOCs could be created as part of the formation process. So, if the ETNOs are formed from a different process than the IOCs, the two populations could have dynamically different origins. It is somewhat difficult to construct a single population that can fulfill the detection statistics of both groups using our observational bias simulator. However, this dearth of objects is only marginally significant due to the small number of known IOCs (Sheppard & Trujillo 2016).

With the discovery of 2015 TG387, we have now found an object that has a perihelion well in the 50–75 au range, and though it is likely stable, it is not as stable as Sedna and 2012 VP113. Thus, it may not be a good object to use in accessing the inner edge of the IOC, as its perihelion may be modified by the action of the galactic tide and passing stars. Nevertheless, we attempted to construct a population that could span both the ETNOs and the IOCs with a \( q' = 4 \) size and \( a = 1 \) semimajor axis distribution and found that the total normalized ratio of objects with \( q \leq 50 \) au, 50 au < \( q < 65 \) au, and \( q \geq 65 \) au was 0.34:0.45:0.21, which departs from the observed distribution of 6:9:2. Assuming binomial counting statistics drawn from our bias simulator, the probability of observing no IOC/ETNO transition objects (0.45 probability per object) in the 50 au < \( q < 65 \) au regime while finding eight objects outside that regime (0.55 probability per object) is 0.0084, the equivalent of a 2.6\( \sigma \) event assuming Gaussian statistics. We also considered the \( a = 2.7 \) semimajor axis power law and found similar results. In this case, the total normalized ratio of objects with \( q \leq 50 \) au, 50 au < \( q < 65 \) au, and \( q \geq 65 \) au was very similar, with 0.21:0.46:0.33. Assuming binomial counting statistics, the probability of observing no objects in the gap region is then 0.0072, the equivalent of 2.7\( \sigma \) assuming Gaussian statistics. Thus, the observation of a “gap” in the 50–65 au regime is not formally statistically significant at the 3\( \sigma \) level without at least two more detections, but it is suggestive of a possible observed gap, or at least a smaller number of objects, in the population between the \( q < 50 \) au ETNO population and the \( q > 65 \) au IOC population. In addition, we note that no other surveys have found objects in this gap region. Although we did not specifically simulate other surveys, this is suggestive that a true gap, or at least a paucity of objects, does exist.

If the perihelion gap between ETNOs and IOCs is confirmed to be real through more discoveries, one possible way the gap may be formed is through resonances with the unobserved distant planet. We know each distant Neptune MMR has a particular favored perihelion distance associated with it. The Plutinos generally come to perihelion around 30 au, while the 5:2 resonance is 32 au, 7:4 is 38 au, and 6:1 is 39 au. In this sense, it is possible the ETNOs and IOCs are in resonances with the distant planet, and these resonances do not generally prefer perihelion in the 50–65 au range. Further modeling and simulations are needed to look at this possibility, though the complicated dynamics and many unknowns might make this only possible to fully analyze once an actual massive planet is found in the outer solar system.

### 4. Simulations of 2015 TG387’s Orbit Stability

We ran several numerical simulations to determine the orbit stability of 2015 TG387 over the age of the solar system under differing conditions. In all simulations, we used the nominal orbit of 2015 TG387 and clones within 3\( \sigma \) of the nominal orbit when including the orbital uncertainties.
4.1. 2015 TG387’s Stability with Known Major Planets

We found that the orbit of 2015 TG387 is very stable when including only the four giant planets and the Sun in our numerical simulations using the Mercury program (Chambers 1999). The semimajor axis, eccentricity, and inclination of 2015 TG387 change little over the age of the solar system (Figure 6). The object’s longitude of perihelion, argument of perihelion, and longitude of the ascending node cycle or precess through $\sim 360^\circ$ from the minor interactions with the quadrupole of the solar system’s potential. For 2015 TG387, the timescale for the argument of perihelion and longitude of perihelion cycle is about 4 and 6.5 Gyr, respectively, when just including the four giant planets. This precession is true for all ETNOs that remain beyond Neptune for their entire orbit, though the cycle timescales differ depending on the object semimajor axis and perihelion distance, as an object with a higher semimajor axis and/or higher perihelion will have less interaction with the known giant planets and thus take longer to precess (Trujillo & Sheppard 2014). See below for a further discussion of the longitude of perihelion and the ETNOs’ precession about these angles for various different simulations.

4.2. 2015 TG387’s Orbit with Galactic Tide

To better understand the long-term dynamical behavior of 2015 TG387 toward forces outside of the solar system, we integrated 100 clones of 2015 TG387 in several simulations with the presence of the known giant planets and Galactic tide for 4 Gyr. We directly integrated the four giant planets as active bodies. The timestep was 200 days. The Galactic tidal model used the same formulation as Levison et al. (2001). In this model, the vertical tide is $\sim 1$ order of magnitude stronger than the radial component. This overall strength of the tide is largely set by the local density of matter in the Galactic disk, which we set to $0.1 \, M_\odot \, pc^{-3}$ (Holmberg & Flynn 2000).

An example of the evolution of one of these clones with the Galactic tide included is shown in Figure 7. We also compare it with the evolution of Sedna, 2012 VP113, and 2014 FE72. As can be seen in the figure, the perihelion of 2015 TG387 can fluctuate by $\sim \pm 10$ au over the course of 4 Gyr due to influence from the Galactic tide. When the 2015 TG387 clone is driven down to a perihelion of $\sim 60$ au, the object begins receiving small energy kicks from the giant planets, driving a minor diffusion in its semimajor axis, which then restabilizes when the perihelion rises above $\sim 60$ au again. In contrast, Sedna has very small changes in perihelion, as its aphelion is only about 1000 au, while 2012 VP113 undergoes almost no changes in perihelion due to its much smaller semimajor axis, which limits the effects of the Galactic tide. Their non-evolving, larger perihelia result in semimajor axes that are virtually fixed with

Figure 6. Evolution of 2015 TG387’s orbital elements with the four known giant planets. The orbital elements for the nominal 2015 TG387 orbit are shown in red. Note that the longitude of perihelion and the argument of perihelion cycle through $\sim 360^\circ$ over the age of the solar system due to the action of the known major planets.

Figure 7. Behavior of different extreme TNOs toward the Galactic tide and four giant planets. Here 2015 TG387 is stable to the Galactic tide, though its perihelion now varies between about 55 and 70 au from Galactic tide interactions. Sedna, with a lower semimajor axis but an aphelion still near 1000 au, has a slight variation in perihelion from the Galactic tide, while 2012 VP113, even more tightly bound, has almost no perihelion variation. The object 2014 FE72 has a larger semimajor axis, and its perihelion is quickly driven down into the giant planet region by the Galactic tide and lost. Notice how 2015 TG387’s semimajor axis only starts to fluctuate when its perihelion is below about 60 au. This is from energy kicks from the giant planets.
time. On the other hand, 2014 FE72 has a much smaller perihelion and a larger semimajor axis than 2015 TG387. Within a couple hundred Myr, its perihelion has moved even closer to the planets, leading to its ejection from the solar system.

The behavior of 2014 FE72 demonstrates that if 2015 TG387 evolves too much in perihelion, its semimajor axis can be inflated via planetary perturbations to the point where it becomes unstable due to wild swings in pericenter driven by the Galactic tide when the semimajor axis is large. However, our integrations of clones demonstrate that such behavior is unlikely for 2015 TG387, as it has a significantly high perihelion and low semimajor axis to prevent major changes to its orbit from both inside and outside forces. Out of our 100 clones, only one was ejected from the solar system over 4 Gyr of evolution (a clone near the 3σ uncertainty limit), and during the last Gyr of integration, any given clone only had a 0.8% chance of having $q < 55$ au.

When including the outside forces from the Galactic tide with the known major planets in our simulations, 2015 TG387’s orbit is mostly stable, though there is a little more movement in its semimajor axis, eccentricity, and inclination from some minor interactions with the Galactic tide than without the Galactic tide simulations. Only a few percent of the clones have significant movement of some 10 au in perihelion and 100 au in semimajor axis over 4 Gyr, but all but one have their perihelia still above 55 au. We consider 2015 TG387 to be stable to the Galactic tide.

4.2.1. The Combination of the Galactic Tide and Solar System’s Quadrupole Moment on the Orbit Stability of ETNOs

Our above results show that outside forces work in tandem with inside forces when an object has a perihelion less than 60 au and a semimajor axis above 1000 au. The amount the Galactic tide affects an ETNO’s orbit is a complicated function of the semimajor axis, inclination, and perihelion distance of the object. The higher the semimajor axis, the more the Galactic tide becomes important, with objects beyond 1000 au starting to have significant interactions with the Galactic tide, as shown by Sedna in Figure 7 (see also Duncan et al. 2008; Kaib & Quinn 2009; Soares & Gomes 2013). If just the Galactic tide was important, one could calculate an object’s perihelion change over time based on the object’s semimajor axis and inclination (see Heisler & Tremaine 1986). But the perihelion distance is also very important for the stability of an object, as once it drops below about 60 au, interactions with the known giant planets become important, as shown by the simulations of 2015 TG387’s orbit (Figure 7). These interactions deliver weak energy kicks, driving a diffusion in semimajor axis. If the semimajor axis increases, then the Galactic tide can drive the perihelion even closer to the planets, generating stronger energy kicks. If the perihelion drops near or below 30–35 au, the object will likely become unstable from strong gravitational interactions with the giant planets, as found for 2014 FE72.

Thus, an object with a higher perihelion but similar distant semimajor axis is more stable, since the object would have similar Galactic tide interactions from outside forces but less interactions with the known giant planets. But there is also the precession effect from the quadrupole moment of the giant planets’ interaction to consider. An object with faster solar system precession of its orbital angles—most importantly, its argument of perihelion, as this angle determines the sign of the Galactic tide perturbation—makes the Galactic tide perihelion perturbation shift from positive to negative and back over time, having a canceling effect on the Galactic tide. The cycling of the argument of perihelion from just the giant planets can be seen in Figure 6, while the fluctuation of the perihelion from the Galactic tide going positive to negative can be seen in Figure 7.

A slow precession of the argument of perihelion, with the critical period being longer than the age of the solar system, will not allow the precessing to suppress net Galactic tide perturbations. Thus, the Galactic tide perturbations just become larger over time, so tidal shifts get larger, causing the perihelion to have larger movement. An object will have a slower precession with a higher perihelion or semimajor axis, since it will interact less with the known inner giant planets.

Though 2015 TG387 is near the limits of stability, it appears to be a mostly stable object. Its semimajor axis and aphelion distance are large enough to cause significant interactions with outside forces, but its perihelion is just high enough that the fluctuations of its perihelion keep it from strongly interacting with the giant planets. If 2015 TG387 had a little lower perihelion distance or a little higher semimajor axis, it would be a much more unstable orbit from the combination of outside and inside forces.

4.3. 2015 TG387’s Orbit with Galactic Tide and Passing Stars

We further ran several simulations that included nearby passing stars, as well as the galactic tide and four known giant planets, for 4 Gyr. The passing star parameters were chosen to be similar to those found in Rickman et al. (2008) and were meant to mimic the conditions of the solar neighborhood. The process of generating random field stars has an inherent element of stochasticity, and the most powerful few stellar encounters will tend to dominate the effects for any large set of encounters (Kaib et al. 2011). We generated four different sets of field star encounters and integrated our 2015 TG387 clones under each set separately. These four simulations are just a small subset of the possible stellar encounter scenarios that could have occurred over the age of the solar system, but they give us a basic understanding of how stable 2015 TG387 is to such encounters. While the range of outcomes for stellar flybys is very large, each of our 4 Gyr simulations represents a compilation of the effects of some 64,000 encounters, as our stellar flyby simulations average about 16 encounters Myr–1, which is near the rate inferred from recent Gaia data (Bailer-Jones et al. 2018). Thus, our four simulations represent about a quarter of a million stellar encounters.

Unlike in the simulations with only the giant planets and the Galactic tide, with stellar encounters, we see that some of the clones have more significant evolution. The four different simulations gave somewhat different results, as our clone survival rates after 4 Gyr of integration for each stellar passage simulation were 99%, 95%, 94%, and 35%. Thus, we do find that there is additional pericenter evolution from passing stars that drives more of our clones into interacting with the giant planets, but the median case still has the vast majority of clones surviving. If we select the 95% survival simulation as our fiducial case, at any given point in the last Gyr of integration, a clone has an ~16% chance of having $q < 50$ au. However, the majority (63%) of our clones maintained a perihelion larger than 50 au for the entire last Gyr of the integration, indicating
that under many stellar passage scenarios, the orbit of 2015 TG387 can remain stable for the age of the solar system. In Figure 8, 2015 TG387 Clone 1 displays the evolution with the moderate stellar encounter scenario where 95% of the 2015 TG387 clones survived, showing minimal changes in the orbit of 2015 TG387 Clone 1 over the age of the solar system.

The other objects’ evolution shown in Figure 8 comes from the simulation with the most powerful set of stellar encounters (35% of the 2015 TG387 clones survived). For 2015 TG387 Clone 2, powerful stellar encounters alter the orbit around ~100 and ~900 Myr (Figure 8). After this, a combination of perturbations from additional stellar passages and the Galactic tide drive Clone 2’s perihelion into the planetary region, where it begins receiving strong energy kicks from the giant planets. This ultimately leads to its ejection after ~3 Gyr. In this particular simulation, behavior like Clone 2’s is not rare, as only 35% of our clones survive the simulation. However, as previously noted, each set of stellar encounters is unique, and their overall cumulative effect is strongly dependent on the few most powerful stellar passages. One can see this when we study the evolution of Sedna and 2012 VP113 in the same simulation (Figure 8). Although Sedna and 2012 VP113 have more strongly bound orbits to the Sun and are generally assumed to be very stable, a particularly powerful set of encounters can elicit some evolution (of order ~5 au) in their perihelia, as was found in Kaib et al. (2011).

4.4. 2015 TG387’s Orbit with a Distant Planet X

Next, we ran simulations to determine if 2015 TG387 could be stable to the possible distant unknown massive planet beyond a few hundred au that may be shepherding the ETNOs into similar types of orbits (Trujillo & Sheppard 2014; Batygin & Brown 2016a). In order to identify where the planet might be in the sky, Trujillo (2019) ran thousands of simulations of a possible distant planet using the orbital constraints put on this planet by Batygin & Brown (2016a). The simulations varied the orbital parameters of the planet to identify orbits where known ETNOs were most stable. Trujillo (2019) found several planet orbits that would keep most of the ETNOs stable for the age of the solar system.

To see if 2015 TG387 would also be stable to a distant planet when the other ETNOs are stable, we used several of the best planet parameters found by Trujillo (2019). In most simulations involving a distant planet, we found that 2015 TG387 is stable for the age of the solar system when the other ETNOs are stable. This is further evidence that the planet exists, as 2015 TG387 was not used in the original Trujillo (2019) analysis but appears to behave similarly as the other ETNOs toward a possible very distant massive planet on an eccentric orbit. In Figure 9, we depict the evolution of 2015 TG387’s orbit with the most favorable distant giant planet orbit from Trujillo (2019), which is simulation number 702b/p335 in Trujillo (2019). The Planet X parameters used in the simulation shown in Figure 9 were $a = 721$ au, $e = 0.55$, $i = 28^\circ.75$, $\omega = 142^\circ$, $\Omega = 93^\circ$, $M = 163^\circ$, and a mass of $10 M_\oplus$. The simulation had a timestep of 8 days and also included the Sun and the four known giant planets.

4.4.1. Longitude of Perihelion Coupled to Planet X

The longitude of perihelion angle for a distant object beyond Neptune will generally precess from the minor gravitational interaction of the object with the quadrupoles of the known major planets. The time to make one complete revolution through the longitude of perihelion angles depends on the object perihelion distance and semimajor axis. The more distant an object’s perihelion and/or semimajor axis, the slower the object will precess in longitude of perihelion. It takes about 1.3 Gyr for 2012 VP113’s longitude of perihelion to precess 360°, while it takes 3.0 Gyr for Sedna. We find that 2015 TG387 takes about 6 billion yr to precess 360° in longitude of perihelion when taking just the known major planets into account. The hypothetical distant massive planet with a perihelion of ~200 au and semimajor axis of ~700 au precesses very slowly in longitude of perihelion because of its distant perihelion and semimajor axis, moving only about 15° over the age of the solar system in longitude of perihelion.

In our simulations where 2015 TG387 was stable with the additional massive distant unknown planet, we found that 2015 TG387 frequently does not precess on a 6 billion yr timescale in longitude of perihelion but librates near its current longitude of perihelion, keeping it mostly antialigned with the hypothetical planet for the age of the solar system. This keeps the object away from crossing the planet’s orbit and thus stable. Amazingly, these distant planet orbits were not chosen to make 2015 TG387 stable but were simply the planet orbits found in
that kept the other ETNOs mostly stable over the age of the solar system. The object 2015 TG387 was only added in the simulations after its orbit was well determined, which was after the Trujillo (2019) simulation results were determined.

It is surprising to find that the third known IOC is stable with the distant massive planet orbits found for the other IOCs and ETNOs; not only is 2015 TG387 stable, but it has resonance behavior with its longitude of perihelion, librating 180° away from, or antialigned with, the planet for the age of the solar system. The argument of perihelion of 2015 TG387 also generally stays near 0° after initially being much higher.

Trujillo (2019) that kept the other ETNOs mostly stable over the age of the solar system. The object 2015 TG387 was only added in the simulations after its orbit was well determined, which was after the Trujillo (2019) simulation results were determined.

It is surprising to find that the third known IOC is stable with the distant massive planet orbits found for the other IOCs and ETNOs; not only is 2015 TG387 stable, but it has resonance behavior with its longitude of perihelion, librating 180° from the planet’s. Planet X also constrains the argument of perihelion of 2015 TG387. As seen in Figure 9, Planet X keeps the argument of perihelion of 2015 TG387 mostly near 0°, just like the clustering seen for the other IOCs and ETNOs first noticed by Trujillo & Sheppard (2014). Though this does not prove that the hypothetical distant planet first realized by Trujillo & Sheppard (2014) and further revealed by Batygin & Brown (2016a) is real, it is strongly suggestive.

We also found that in most of the dynamical simulations with Planet X, some 2015 TG387 clones became retrograde while still being in a stable orbit in resonance with the hypothesized planet, with the longitude of perihelion still constrained to be antialigned with the planet (Figure 10). Thus, finding retrograde ETNOs could be a further signature of Planet X if they too are clustered into certain orbital configurations. This also suggests that the distant planet itself could be on a retrograde orbit. To test this theory, we reran all of our simulations that involved Planet X, but this time we put the distant planet on a retrograde orbit, with all other variables being the same. This involved changing the Planet X orbital elements’ inclination to \( i_{\text{retrograde}} = 180° - i_{\text{prograde}} \), longitude of the ascending node to \( \Omega_{\text{retrograde}} = 180° - \Omega_{\text{prograde}} \), argument of perihelion to \( \omega_{\text{retrograde}} = 180° - \omega_{\text{prograde}} \), and mean anomaly to \( M_{\text{retrograde}} = -M_{\text{prograde}} \). We found that 2015 TG387 behaves very similarly to a retrograde Planet X as it does to a prograde Planet X (Figure 11). Even with a retrograde Planet X, 2015 TG387 continues to be stable and confined in longitude of perihelion and argument of perihelion angles. We found that this is true for all of the ETNOs.

4.5. Stability of 2015 TG387 with Planet X, Galactic Tides, and Passing Stars

When adding in Galactic tides with the simulations involving 2015 TG387 and a distant planet, we find that most clones of 2015 TG387 continue to librate in longitude of perihelion. Thus, Galactic tides are not a destabilizing force to 2015 TG387’s libration in longitude of perihelion with the planet.
In the passing stars case, where outside perturbations can be much stronger and stochastic, we also find a large percentage of 2015 TG387 clones librating in longitude of perihelion with the planet for the age of the solar system. In a 4 Gyr simulation using our fiducial 95% 2015 TG387 clone survival stellar encounter set with the Galactic tide and a distant planet, we find that the survival fraction of 2015 TG387 clones drops to 72%. However, of those surviving clones, 68% have a longitude of perihelion that is within \( \pm 45^\circ \) of being exactly antialigned with the planet’s longitude of perihelion \( \sim 180^\circ \) away, showing that the surviving 2015 TG387 clones are the ones that have longitude of perihelion resonance with the planet, as found in the previous Planet X simulations.

5. Summary

We discovered a new trans-Plutonian object or IOC, 2015 TG387, that has the third-highest perihelion of any known object to date at 65 \( \pm 1 \) au. It was discovered in our ongoing survey for objects beyond 50 au, which has now covered 2130 deg\(^2\) of sky mostly using the Subaru 8 m and Blanco 4 m telescopes. Assuming a moderate albedo, the diameter of 2015 TG387 is about 300 km. The details of this new discovery are as follows.

1. The longitude of perihelion of 59° for 2015 TG387 is similar to that for Sedna, 2012 VP113, and the other ETNOs. Using only the low observationally biased discovered IOCs and detached ETNOs from our survey, as well as Sedna, finds the longitude of perihelion clustering only about a 2\(\sigma\)–2.5\(\sigma\) significance. The significance of the clustering is not at the 3\(\sigma\) level because only four objects are being used that have low observational biases in their longitude discovery (Sedna, 2012 VP113, 2015 TG387, and 2014 SR349). Using all eight of the known IOCs and detached ETNOs gives a significance of \( \sim 3\sigma \) in longitude of perihelion clustering, but this ignores the longitude biases in the discovery of many of these objects. Several more IOCs and detached ETNOs need to be discovered in uniform longitude surveys to obtain a good statistical analysis of the population’s longitude of perihelion clustering.

The longitude of perihelion clustering continues to be an interesting trend to watch.

2. With the discovery of 2015 TG387, we find that the semimajor axis distribution of the IOCs is likely an \( a^{2.5} \) distribution. That is, there are many more IOCs with high semimajor axes than low semimajor axes. If the power-law slope of the semimajor axis distribution is near 3, as we suggest, this implies a fairly constant space density of objects moving outward with distance, since the volume of space goes as the cube of distance.

3. The total number of IOCs larger than 40 km in diameter is about \( 2 \times 10^6 \), giving a total mass of about \( 10^{22} \) kg. This makes the IOC population similar in mass to the Kuiper Belt population when using a size distribution, as shown in Sheppard & Trujillo (2016).

4. The IOCs and detached ETNOs appear to have an inclination distribution similar to the scattered disk population of TNOs, with an average inclination around 19°. The IOCs do not appear to have a narrow (like the classical KBOs) or very thick (like the MMR-KR TNOs) inclination distribution, as most have inclinations between about 10° and 25° inclination.

5. When just simulating the known planets in our solar system, 2015 TG387 has a very stable orbit. The orbit is also fairly stable when including the Galactic tide. Including passing stars over the age of the solar system usually finds 2015 TG387 to be stable as well, but it is dependent on the stellar encounter scenario used. In most stellar encounter scenarios, some 95% of the 2015 TG387 clones are stable for the age of the solar system. But in the strongest stellar encounter scenario used, some 65% of the 2015 TG387 clones are lost over the age of the solar system. Overall, 2015 TG387 appears to be on an orbit that most likely has lasted the age of the solar system near its current orbital parameters.

6. We find that the outside force of the Galactic tide and inside force of the quadrupole moment of the solar system work in tandem to effect 2015 TG387’s orbit. The Galactic tide becomes important beyond about 1000 au, as seen in Sedna’s orbit evolution. The quadrupole moment of the solar system is important when the precession of the angle of argument of perihelion of an object’s orbit is slow enough that the Galactic tide perturbations continually increase until an object’s perihelion is pushed interior to about 60 au. Once an object has a perihelion interior to \( \sim 60 \) au, significant energy kicks from the known giant planets cause the object’s semimajor axis to change. This change in semimajor axis can have increased energy kicks from the giant planets that can further lower the perihelion of an object until it starts to more strongly interact with the Galactic tide and a distant planet, we using our fiducial 95% 2015 TG387 clone survival stellar encounter set with the Galactic tide and a distant planet, we find that the survival fraction of 2015 TG387 clones drops to 72%. However, of those surviving clones, 68% have a longitude of perihelion that is within \( \pm 45^\circ \) of being exactly antialigned with the planet’s longitude of perihelion \( \sim 180^\circ \) away, showing that the surviving 2015 TG387 clones are the ones that have longitude of perihelion resonance with the planet, as found in the previous Planet X simulations.

5. Summary

We discovered a new trans-Plutonian object or IOC, 2015 TG387, that has the third-highest perihelion of any known object to date at 65 \( \pm 1 \) au. It was discovered in our ongoing survey for objects beyond 50 au, which has now covered 2130 deg\(^2\) of sky mostly using the Subaru 8 m and Blanco 4 m telescopes. Assuming a moderate albedo, the diameter of 2015 TG387 is about 300 km. The details of this new discovery are as follows.
with the giant planets. Once the perihelion of an object is around 30–35 au or lower, the object will likely become unstable from gravitational scattering off the giant planets. Because it is near the perturbations from both inside and outside forces, 2015 TG387 is near the edge of stability. That is, 2015 TG387’s perihelion is just high enough that interactions with the giant planets are not significant, though its semimajor axis is just large enough that Galactic tide perturbations can push 2015 TG387’s perihelion a little interior to 60 au, causing slight semimajor axis variations. But as 2015 TG387’s argument of perihelion precesses from interactions with the quadrupole moment of the solar system, the perihelion of 2015 TG387 will rise back above 60 au before any significant changes in its orbit from giant planet energy kicks while it has a perihelion below 60 au. If 2015 TG387 had a little closer perihelion or a little larger semimajor axis, it would become more unstable, as it would be pushed into interacting more with the giant planets. If an object gets its perihelion pushed down to around 30–35 au or lower, it will become unstable from strong gravitational interactions with the giant planets. Thus, objects that have moderate semimajor axes and are generally thought to be stable in the inner Oort cloud (1000–2000 au) can still become unstabilized fairly easily if they have perihelia that can be pushed well below about 60 au from a combination of outside and inside forces. The main cause of an ETNO or IOC obtaining an unstable orbit is the strong interactions it can have with the giant planets when its perihelion is eventually pushed to around 30 au or less.

(7) When including a massive Planet X at several hundred au, as predicted by Trujillo & Sheppard (2014), with the eccentric and inclined rudimentary orbit proposed for it by Batygin & Brown (2016a) in our simulations, we find that 2015 TG387 is usually stable to such a planet when the other IOCs and ETNOs are also stable. Amazingly, in most simulations with a Planet X, we found that 2015 TG387 librates in its longitude or perihelion, keeping it antialigned and thus stable with the eccentric Planet X for the age of the solar system. This longitude of perihelion libration is not seen in the simulations without a Planet X. Further, Planet X also constrains the argument of perihelion of 2015 TG387 and actually keeps it mostly near 0° in our simulation shown in Figure 9, just like the current argument of perihelia of the other known IOCs and ETNOs. These results support the theory that a Planet X exists, as 2015 TG387’s orbit was only determined after the basics of the Planet X orbit were realized, yet 2015 TG387 reacts with the planet very similarly to the other known IOCs and ETNOs. In addition, some 2015 TG387 clones obtain retrograde orbits yet still remain stable and antialigned with Planet X for the age of the solar system, suggesting that retrograde ETNOs should exist in most Planet X scenarios. We further found that the planet itself might be on a retrograde orbit, as 2015 TG387 and other ETNOs were similarly stable as in the prograde planet case.

Based in part on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. Observations were partly obtained at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation. This project used data obtained with the Dark Energy Camera (DECam), which was constructed by the Dark Energy Survey (DES) collaborating institutions: Argonne National Lab, the University of California Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil consortium, the University of Edinburgh, ETH-Zurich, the University of Illinois at Urbana-Champaign, Institut de Ciencies de l’Espai, Institut de Física d’Altes Energies, Lawrence Berkeley National Lab, Ludwig-Maximilians University, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Lab, Stanford University, the University of Sussex, and Texas A&M University. Funding for DES, including DECam, has been provided by the U.S. Department of Energy, National Science Foundation, Ministry of Education and Science (Spain), Science and Technology Facilities Council (UK), Higher Education Funding Council (England), National Center for Supercomputing Applications, Kavli Institute for Cosmological Physics, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo a Pesquisa, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência e Tecnologia (Brazil), the German Research Foundation–sponsored cluster of excellence “Origin and Structure of the Universe,” and the DES collaborating institutions. N.A.K. received funding from NASA’s Emerging Worlds program (grant 80NSSC18K0600) and computational support through the OU Supercomputing Center for Education and Research (OSCER) at the University of Oklahoma (OU). This paper includes data gathered with the 6.5 m Megellan telescopes located at Las Campanas Observatory, Chile. This research was funded by NASA Planetary Astronomy grant NN15AF446.

ORCID iDs
Scott S. Sheppard @ https://orcid.org/0000-0003-3145-8682
Chadwick A. Trujillo @ https://orcid.org/0000-0001-9859-0894

References
Bailer-Jones, C., Rybizki, J., Andrae, R., & Foushee, M. 2018, A&A, 616, 37
Bailey, E., Brown, M., & Batygin, C. 2018, AJ, 156, 74
Bannister, M., Shankman, C., Volk, K., et al. 2017, AJ, 153, 262
Batygin, K., & Brown, M. 2016a, AJ, 151, 22
Batygin, K., & Brown, M. 2016b, ApJ, 833, 3
Batygin, K., & Morbidelli, A. 2017, AJ, 154, 229
Becker, J., Adams, F., Khain, T., Hamilton, S., & Gerdes, D. 2017, AJ, 154, 61
Becker, J., Khain, T., Hamilton, S., et al. 2018, AJ, 156, 81
Brasser, R., Duncan, M., Levison, H., Schwamb, M., & Brown, M. 2012, Icar, 217, 1
Brasser, R., & Schwamb, M. 2015, MNRAS, 446, 3788
Brown, M. 2008, in The Solar System Beyond Neptune, ed. M. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 335
Brown, M. 2017, AJ, 154, 65
Brown, M., & Batygin, K. 2016, ApJ, 824, 23
Brown, M., Trujillo, C., & Rabinowitz, D. 2004, ApJ, 617, 645
Chambers, J. 1999, MNRAS, 304, 793
Duncan, M., Brasser, R., Dones, L., & Levison, H. 2008, in The Solar System Beyond Neptune, ed. M. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 315
Fernandez, J. 1997, Icar, 129, 106
Flahuger, B., Diehl, H., Honncheid, K., et al. 2015, AJ, 150, 150
Fraser, W., Morbidelli, A., Parker, A., & Batygin, K. 2014, ApJ, 782, 100
