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Analysis of trans-Neptunian objects and a proposed theory to explain their origin

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ABSTRACT

Current theories cannot explain how trans-Neptunian objects (TNOs) either formed *in situ* or how ultrawide trans-Neptunian binaries (TNBs) exist if they were formed closer to the Sun and were later dispersed during Neptune's migration. Furthermore, no theory can adequately explain the documented clustering of ω near 0° for TNOs with $a > 150$ au. Here, we show that not only is ω clustered for the nine long-period TNOs (LPTNOs) with $a > 200$ au, but Ω is also grouped almost as closely. Neither of these orbital elements is randomly distributed for any collection of TNOs investigated, including those that are not in resonance with Neptune, those with $q > 30$ au, $q > 44$ au, and LPTNOs. Every frequency distribution of ω and Ω indicates that many TNOs were recently affected by Neptune. Based on this study, we propose that TNOs were inside Neptune's orbit in the last few Myr. The TNOs then migrated outwards in a relatively short time period. Ultrawide TNBs never came close to Neptune during this migration, allowing these fragile pairs to remain intact. However, many other TNOs were perturbed as they passed Neptune, resulting in the distribution of orbital elements we see today for all TNOs, including those in the Kuiper belt and the LPTNOs.

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

1 INTRODUCTION

The Kuiper belt, ranging from 30 au to approximately 50 au, is home to an estimated 70 000 trans-Neptunian objects (TNOs) (Iorio 2007). There are many theories on the origin of these bodies, all of which assume that TNOs have been in their present location for billions of years. Each of these theories has at least one significant problem.

One theory proposes that Kuiper belt TNOs formed *in situ* from planetesimals fragments that remained after the formation of the Solar system. However, the cloud of planetesimals at that distance from the Sun would have been too dispersed to have coalesced (Lemonick 2014). Another prominent theory postulates that these TNOs formed closer to the Sun. Then, shortly after the Solar system formed, Neptune migrated outwards, scattering all these objects into their present location (Levison & Morbidelli 2003; Levison et al. 2008). This theory cannot, however, explain how ultrawide trans-Neptunian binaries (TNBs) exist in the Kuiper belt (Margot 2002; Pettit et al. 2008; Parker et al. 2011). These loosely bound, paired objects should have been separated if they were perturbed by Neptune. A third possibly is TNOs formed in their present location from collisions. This theory has other problems. Collisions beyond Neptune would be too infrequent, and if collisions did occur, they would likely separate the wide binaries (Goldreich, Lithwick & Sari 2002; Weidenschilling 2002).

It is even more difficult to explain the origins of TNOs beyond the Kuiper belt. Sedna, located in the inner Oort cloud, is especially perplexing (Brown, Trujillo & Rabinowitz 2004). With a perihelion of 76 au, it is well beyond the influence of Neptune, which orbits at 30 au. Sedna also travels out to a distance of almost 1000 au from the Sun, which is thousands of astronomical units short of the proposed Oort cloud (Schwamb 2014). Many theories have been proposed for the origin of this strange body, all of which assume that Sedna has been in its present orbit for billions of years (Morbidelli & Levison 2004).

The origin of Sedna became much more difficult to explain after the discovery of 2012 VP_{113}, with a perihelion of 80 au (Trujillo & Sheppard 2014). Not only is this asteroid comparable to Sedna, but Trujillo & Sheppard (2014) also noticed that almost all the TNOs with a semimajor axis greater than 150 au have an argument of perihelion near 0°. They determined that this was not due to observational bias, and Galactic tides could not have produced these strange orbits. Instead, they postulated that the Lidov–Kozai effect created these orbits shortly after the formation of the Solar system (Kozai 1962). However, they noted two problems with this theory. First, the Lidov–Kozai effect would cause ω to be clustered near 180° as well, not just 0° (Brasser, Duncan & Levison 2006). Also, after just a few Myr, ω would be randomly distributed due to small perturbations from the giant planets (Jíková et al. 2015). To explain

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Table 1. Parameters for the nine LPTNOs, with $q > 30$ au and $a > 200$ au, sorted by q. Data were collected from the Jet Propulsion Laboratory (JPL) small-body database on 2015 September 18 with epochs of 2015 June 27.

Object	a (au)	e	i (°)	ω (°)	Ω (°)	q (au)
2012 VP_{113}	263.12	0.69	24.02	− 66.17	90.87	80.51
(90377) Sedna	524.43	0.85	11.93	− 48.71	144.55	76.09
2010 GB_{174}	370.19	0.87	21.53	− 12.35	130.59	48.63
2004 VN_{112}	328.86	0.86	25.54	− 32.78	66.04	47.33
2000 CR_{105}	229.83	0.81	22.71	− 42.83	128.23	44.24
2013 RF_{98}	316.51	0.88	29.59	− 43.46	67.55	36.29
2007 TG_{422}	518.17	0.93	18.58	− 74.17	112.98	35.58
2002 GB_{32}	211.64	0.84	14.18	36.90	177.00	35.34
2001 FP_{185}	222.87	0.85	30.77	6.84	179.32	34.24

this second problem, Trujillo & Sheppard (2014) postulated that there is an undiscovered, super planet located approximately 250 au from the Sun, which constrains ω near 0° for TNOs with $a > 150$ au. An independent examination of these orbits noted that their inclinations are also clustered near 20°. This study also confirmed that the clustering of these orbital elements is not due to statistical coincidence or observational bias. These authors strongly suggested a need for at least two giant planets beyond Pluto to account for the clustering of ω near 0° (de la Fuente & de la Fuente 2014). However, they still were unable to explain how these TNOs initially obtained arguments of perihelion near 0°, and not near 180°.

More recently, Iorio (2014) concluded that the possibility of a super planet beyond 200 au 'faces serious observational challenges' due to constraints on the precession of ω for some of the known planets in our Solar system. Others have suggested that TNO orbits beyond 150 au were caused by a close pass of a giant star (Kenyon & Bromley 2004; Jíková et al. 2015) or perhaps their orbits were altered during a time of solar migration within the Galaxy (Brasser & Schwamb 2014). None of these theories, though, can explain why ω is clustered close to 0° (and not 180°) or what has kept ω near 0° for billions of years.

2 ω AND Ω FOR LONG-PERIOD TNOS

In this paper, we begin our investigation by examining the orbital elements of long-period TNOs (LPTNOs), defined here to have $q > 30$ au and $a > 200$ au. There are nine known LPTNOs, which are listed in Table 1 in decreasing order of q. They all have periods of more than 3000 yr, and their inclinations are all within $22.7 \pm 9.4°$.

Fig. 1(a) shows the distribution of argument of perihelion as a function of semimajor axis for all 1552 known TNOs with $q > 30$ au. The LPTNOs, listed in Table 1, are depicted with large circles in Fig. 1(a). These nine LPTNOs all have $\omega = -18.6° \pm 55.5°$, with a mean of $-30.7°$. A Monte Carlo simulation using 10 million trials determined the probability of nine random angles clustering this close together is 0.07 per cent. Fig. 1(a) is very similar to fig. 3 from Trujillo & Sheppard (2014). The most significant difference is that they looked at the clustering of ω for TNOs with $a > 150$ au. For these TNOs, 14 of the 15 orbits have an argument of perihelion clustered within $-16.0° \pm 58.2°$, which is also extremely unlikely. As previously mentioned, no theory can adequately explain why these TNOs have a bias for ω near approximately $-25°$ or why they have not drifted apart over billions of years.

In addition to the clustering of arguments of perihelion, we also discovered that the right ascensions of the ascending node are clustered almost as closely for this same group of LPTNOs. This is shown in Fig. 1(b), which depicts the distribution of Ω as a function of semimajor axis for all TNOs with $q > 30$ au. Similar to Fig. 1(a), the LPTNOs are shown with large circles. These all fall within the range of $122.7° \pm 56.6°$ and have a mean of 121.9°. A Monte Carlo simulation revealed the probability of random angles clustering this close is only 0.09 per cent. This poses additional problems for every theory that attempts to explain the origin of these LPTNOs. If large planets exist beyond Neptune, the Lidov–Kozai effect could have kept Ω clustered, just like ω, only with different periods of oscillation (Kinoshita & Nakai 2007). However, it is unknown how many hypothesized planets would be required to constrain both orbital elements. More importantly, Iorio (2014) showed the presence of super planets beyond 200 au is 'strongly disfavoured'. Without such a mechanism to keep ω and Ω clustered, small differences in perturbations should have resulted in a random distribution of these orbital elements in just a few Myr (Jíková et al. 2015). In addition, there is no current explanation why Ω would be initially clustered near 123°.

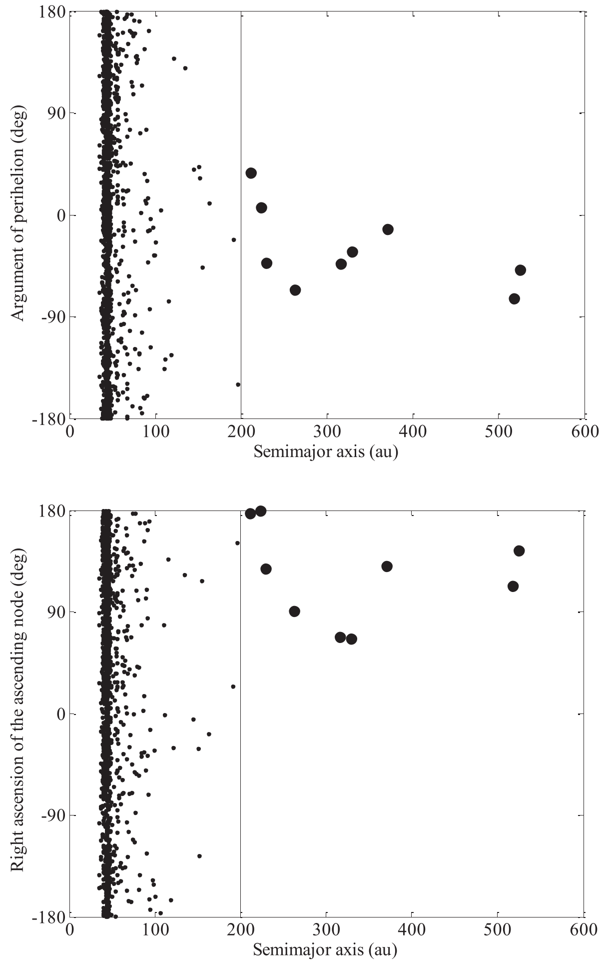

Figure 1. Orbital parameters of all TNOs with $q > 30$ au as a function of semimajor axis. The large circles represent the nine LPTNOs. The top panel shows that these LPTNOs have arguments of perihelion of $-18.6° \pm 55.5°$. If these are random orbits, the probability of this close of a clustering is 0.07 per cent. The bottom panel shows the right ascensions of the ascending node for the same nine LPTNOs are all $122.7° \pm 56.6°$. The probability of this happening by chance is 0.09 per cent.

Fig. 2(a) combines much of the data in Figs 1(a) and (b). This figure shows the right ascension of the ascending node as a function of argument of perihelion for all known TNOs with $q > 30$ au. As in Fig. 1, the LPTNOs are represented with nine large circles. The

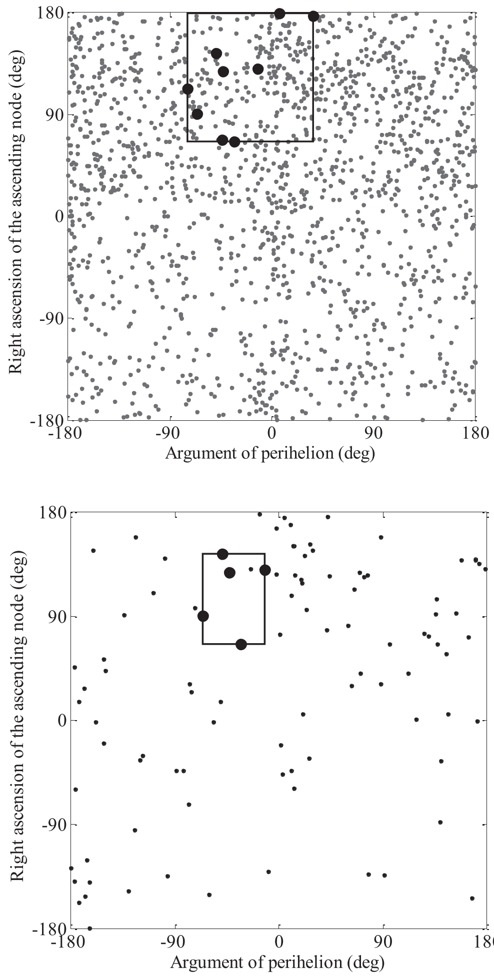

Figure 2. Right ascension of the ascending node as a function of argument of perihelion for TNOs with $q > 30$ au (top panel) and $q > 44$ au (bottom panel). The large circles represent the LPTNOs with $a > 200$ au. All nine of the LPTNOs have parameters that fall inside the rectangle in the top panel, and all five fall inside the rectangle in the bottom panel. The probability of this happening by chance is 0.005 and 0.04 per cent, respectively.

parameters for all of these LPTNOs fall within the small rectangle shown in Fig. 2(a). A Monte Carlo simulation showed that if the values for ω and Ω came from independent, random events, the probability of all of them falling in this small of a rectangle is only 0.005 per cent.

Although this data clearly indicate that these are not random orbits, Trujillo & Sheppard (2014) speculated that perhaps objects with q less than 44 or possibly 45 au could be affected by Neptune's gravity. We agree that these LPTNOs may have been affected by Neptune in the past, but since their orbits all have periods of 3000 yr or more, it is doubtful that Neptune affects any of these orbits today. Nevertheless, to rule out the possibility of Neptune's influence, we evaluated the subset of TNOs with $q > 44$ au. This is fairly conservative, considering other authors use $q > 40$ au as the point where Neptune no longer affects TNOs gravitationally (Gladman et al. 2002; Lykawka & Mukai 2007; Lykawka 2012). Fig. 2(b) is the same plot as Fig. 2(a), showing only these limited numbers of TNOs. In this case, there are only five LPTNOs with $q > 44$ au, which are listed in the first five rows of Table 1. These LPTNOs have values for ω and Ω that fall within an even smaller rectangle shown in Fig. 2(b). A Monte Carlo simulation revealed the probability of

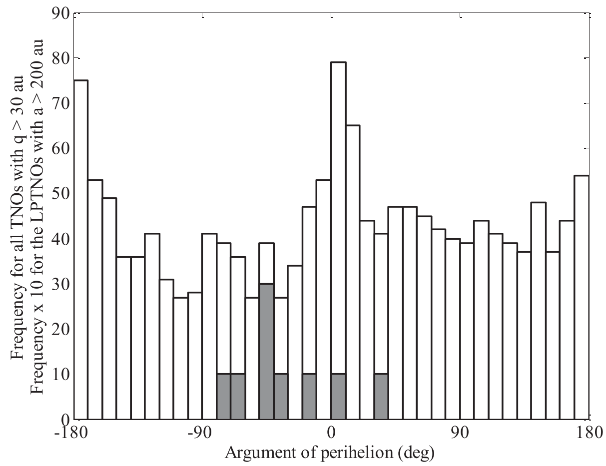

Figure 3. Frequency distribution of argument of perihelion for all TNOs with $q > 30$ au (white bars) and 10 times the frequency for the LPTNOs with $a > 200$ au (grey bars). The frequency distribution for all TNOs beyond 30 au has pronounced peaks at $\omega = 0°$ and 180°. The distribution of the nine LPTNOs with $a > 200$ au is shifted to the left of 0°, with an average of $-30.7°$. Using a K–S test, the hypothesis that these two distributions came from the same continuous distribution could not be rejected ($\alpha = 0.01$, p-value $= 0.09$).

random angles falling within a rectangle of this size is only 0.04 per cent. If we had used $q > 47$ au (instead of $q > 44$ au) as the threshold where Neptune no longer affects these LPTNOs, there would have been only four large circles inside the rectangle in Fig. 2(b). The final results would have still been very unusual, with a statistical probability of only 0.5 per cent. Either way, this close clustering of ω and Ω for LPTNOs with $a > 200$ au is extremely rare. Also, because Fig. 2(b) only includes TNOs with $q > 44$ au, the gravitational attraction of Neptune alone cannot account for this clustering. These LPTNOs are likely not independent. Perhaps instead, they were all affected by the same event in the recent past.

3 FREQUENCY DISTRIBUTIONS OF ω

To better formulate a theory regarding this unusual clustering of orbital elements for LPTNOs, we first investigated the distribution of ω for all TNOs with $q > 30$ au. We began by looking at the same data in Fig. 1(a) using a histogram format. This is shown in Fig. 3, which is a frequency distribution of ω for all 1552 known TNOs with perihelion greater than 30 au (white bars). The grey bars show the distribution of ω for the nine LPTNOs discussed in Section 2 with the frequencies magnified by a factor of 10 to make them more visible.

There are pronounced peaks very close to 0° and 180° when considering the entire population of TNOs with $q > 30$ au (white bars). Stated another way, a majority of TNOs with $q > 30$ au have perihelion near the plane of the ecliptic. If perihelion is close to where the orbit moves from south to north through this plane, ω is close to 0°. If instead, perihelion is close to where the orbit moves from north to south, ω is close to 180°. This would be expected if something near the plane of the ecliptic recently perturbed many of the TNOs.

In comparison, the LPTNOs have ω clustered only close to 0°, and none near 180° (grey bars in Fig. 3). To be more precise they are all clustered within $-18.6° \pm 55.5°$, with a mean of $-30.7°$. None of these LPTNOs has an ω close to 180°, meaning their perihelions are only close to the plane of the ecliptic as the orbit moves from south

Table 2. 591 TNOs with $q > 30$ au are possibly in resonance with Neptune. These TNOs were eliminated from further analysis in this paper.

Resonance	Calculated period for resonance (yr)	Periods of TNOs that were eliminated (yr)	Number of TNOs eliminated
4:5	206.0	204–207	2
3: 4	219.7	219–221	7
2:3	247.2	242–250	183
3:5	274.7	273–279	86
4:7	288.4	286–291	156
5:9	296.6	296–298	35
1:2	329.6	326–371	47
4:9	370.8	368–371	3
3:7	384.5	384–393	11
5:12	395.5	393–402	9
2:5	412.0	408–415	21
3:8	439.5	438–446	3
1:3	494.4	490–505	11
3:10	549.3	546–552	6
2:7	576.8	565–584	4
1:4	659.2	659–661	3
1:5	824.0	820–858	4

to north. Despite this difference, a Kolmogorov–Smirnov (K–S) test was unable to reject the hypothesis that these two distributions came from the same continuous distribution ($\alpha = 0.01$, p-value $= 0.09$), meaning it is very plausible that they are from the same distribution.

Although, the two peaks at 0° and 180° in Fig. 3 are interesting, we suspected this frequency distribution could be biased. Many of these TNOs may be in resonance with Neptune, and after long periods of time, this could certainly affect their orbits and keep many of their perihelions close to the plane of the ecliptic. To eliminate this potential bias, we identified all the TNOs with $q > 30$ au that might be in resonance with Neptune (Chiang & Jordan 2002; Chiang et al. 2004; Lykawka & Mukai 2007; Pike et al. 2015). These are shown in Table 2. The first two columns list the ratio of periods and exact period that would be in resonance with Neptune. The third column identifies the periods of the TNOs that were eliminated from further study, and the fourth column shows how many TNOs had periods within this range and were eliminated. There were a total of 591 TNOs with $q > 30$ au that we excluded from further study. This is greater than the number of TNOs known to be in resonance with Neptune, but we wanted to also exclude TNOs with periods that could possibly result in resonance (Lykawka & Mukai 2007).

There is another potential bias in Fig. 3. Many of the 1552 TNOs included in this figure have orbits that are circular or are very close to a circle. Because a circular orbit does not have a perihelion, ω is undefined. For orbits that are nearly circular, ω is almost undefined, and it is somewhat irrelevant because small perturbations can drastically change ω. According to JPL's small-body database (2015), of the 1552 TNOs included in Fig. 3, 379 have an eccentricity less than 0.05. We thought it would be best to also exclude these nearly circular orbits from any frequency distributions of ω.

After eliminating TNOs identified in Table 2, that might be in resonance with Neptune, and also disregarding the near-circular orbits ($e < 0.05$), there were 697 TNOs remaining with $q > 30$ au. Fig. 4 shows the frequency distribution of ω for these TNOs (white bars). There are still two noticeable peaks very close to 0° and 180°. A chi-squared goodness of fit test confirmed this data did not come from random samples of a uniform distribution ($\alpha = 0.01$, p-value $= 0.004$). Another chi-squared test was unable to reject the hypothesis that this frequency distribution came from overlapping normal distributions with means of 0° and 180° and standard deviations of deviations of 60° ($\alpha = 0.01$, p-value $= 0.43$). This continuous function is shown with the curved, black line in Fig. 4. As before, the grey bars show 10 times the frequency distribution of ω for the nine LPTNOs. Their arguments of perihelion are centred on −18.6° with a mean of −30.7°. A K–S test was unable to reject the hypothesis that the two distributions shown in Fig. 4 came from the same continuous distribution ($\alpha = 0.01$, p-value $= 0.10$).

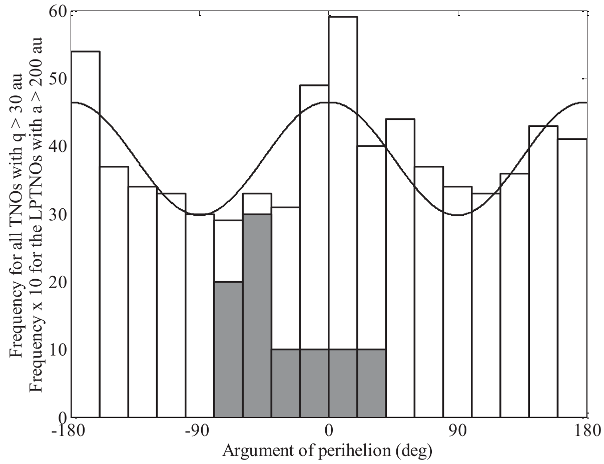

Figure 4. Frequency distribution of argument of perihelion for all 697 TNOs with $q > 30$ au, which are not in resonance with Neptune and have $e > 0.05$ (white bars). This distribution also has peaks at 0° and 180°. A chi-squared test showed that this is not a random distribution ($\alpha = 0.01$, p-value $= 0.004$). Another chi-squared test was used to see if this distribution could have come from a population of two overlapping normal distributions, with means of 0° and 180° and standard deviations of 60° (shown with a curved black line). This hypothesis could not be rejected ($\alpha = 0.01$, p-value $= 0.43$). The grey bars show 10 times the frequency of ω for the LPTNOs with $a > 200$ au. A K–S test showed that this could have come from the same distribution as the 697 TNOs shown with the white bars ($\alpha = 0.01$, p-values $= 0.10$).

Therefore, it is reasonable to conclude that ω is not randomly distributed for TNOs, even after disregarding orbits that are almost circular or might be in resonance with Neptune. Instead, for TNOs with $q > 30$ au, ω can be accurately modelled as overlapping normal distributions with means of 0° and 180° and standard deviations of 60°. Also, the distribution of ω for LPTNOs could have come from this same population despite the fact that none of the LPTNOs has an ω close to 180° and all their arguments of perihelion are clustered about 25° lower than 0°.

We also investigated the frequency distribution of ω for TNOs that are never close to Neptune's orbit. We decided to use the same threshold as in Fig. 2(b) and only include TNOs with $q > 44$ au. Fig. 5 shows this frequency distribution. Unfortunately, after eliminating TNOs that might be in resonance with Neptune or are close to a circle, there are only 10 TNOs with $q > 44$ au (white bars in Fig. 5, which include the area under the grey bars). Despite this small sample size, there are still two noticeable groups. There are no TNOs in this plot with ω between −150° and −90° or between 30° and 120°. The seven TNOs shown near the middle of the plot have an average ω of −27°. The other three TNOs have an average ω of 167°. These values are approximately 25° lower than the two peaks of 0° and 180° found for the TNOs beyond 30 au, in Figs 3 and 4. The grey bars in Fig. 5 show the five LPTNOs with $q > 44$ au, which are the same data points represented as large circles in Fig. 2(b) and also the first five rows in Table 1. These LPTNOs all have a semimajor

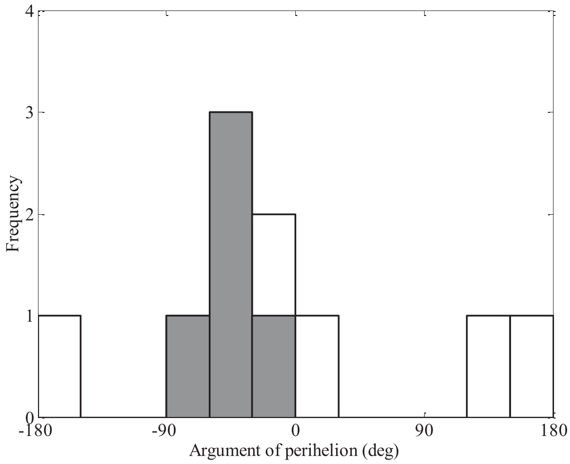

Figure 5. Frequency distribution of argument of perihelion for all 10 TNOs with $q > 44$ au, which are not in resonance with Neptune and have $e > 0.05$ (white bars). As in Figs 3 and 4, there are two groups. Only here their mean values are $-27°$ and $167°$, which are about $25°$ lower than the two peaks of $0°$ and $180°$ in Figs 3 and 4. Despite this dissimilarity, no statistical differences between this distribution and the ones in Figs 3 and 4 were found using a K–S test ($\alpha = 0.01$, p-values = 0.42 and 0.46, respectively). The grey bars show the distribution of the five LPTNOs with $q > 44$ au. They have a similar distribution as all the TNOs with $q > 44$ au. The most obvious difference is that no LPTNO has an ω close to $180°$. Despite this distinction, no statistical difference was found between the grey and white distributions in this figure using a K–S test ($\alpha = 0.01$, p-value = 0.54).

axis greater than 229 au. This is considerably larger than the other five TNOs included in this figure, which all have a semimajor axis of less than 77 au.

Fig. 5 did not have enough samples to conduct a chi-squared goodness of fit test. However, the data do not appear to be randomly distributed. Also, no difference was found between the white bars in Fig. 5 and those in Figs 3 and 4 using a K–S test ($\alpha = 0.01$, p-values = 0.42 and 0.46, respectively). There was also no statistical difference found between the grey and white distributions shown in Fig. 5 ($\alpha = 0.01$, p-value = 0.54).

Although the white bars in Figs 3–5 are statistically similar, we discovered that a significantly higher percentage of TNOs have an eccentricity less than 0.05 when $q > 44$ au. Of the 1453 known TNOs with q between 30 and 44 au, 20 per cent are close to a circle. In comparison, 88 per cent of the 99 TNOs with $q > 44$ au are almost a circle. This is a remarkable difference. If we only considered those TNOs that are extremely close to a circular orbit (defined here to be $e < 0.0001$), there is an even bigger difference. In this case, only 4 per cent of the TNOs with q between 30 and 44 au have an eccentricity this small, compared to 49 per cent of those with $q > 44$ au. Any formation mechanism, proposed for the origin of TNOs, should be able to explain the frequency distributions displayed in Figs 4 and 5, and ideally it should also explain why TNOs with larger perihelion distances are much more likely to be circular.

4 FREQUENCY DISTRIBUTIONS OF Ω

A similar process was used to examine the clustering of Ω for the LPTNOs shown in Fig. 1b. First, we examined the frequency distribution of Ω for all 1552 known TNOs with $q > 30$ au. This is presented in Fig. 6 (white bars). The grey bars show 10 times the frequency distribution of Ω for the nine LPTNOs, which are

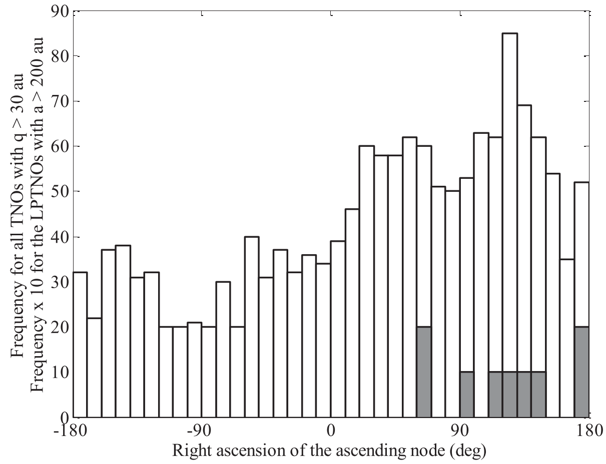

Figure 6. Frequency distribution of right ascension of the ascending node for all TNOs with $q > 30$ au (white bars) and 10 times the frequency for the LPTNOs with $a > 200$ au (grey bars). The white bars have a pronounced peak around 120°–140°, and the average value of Ω for the LPTNOs is 122°.

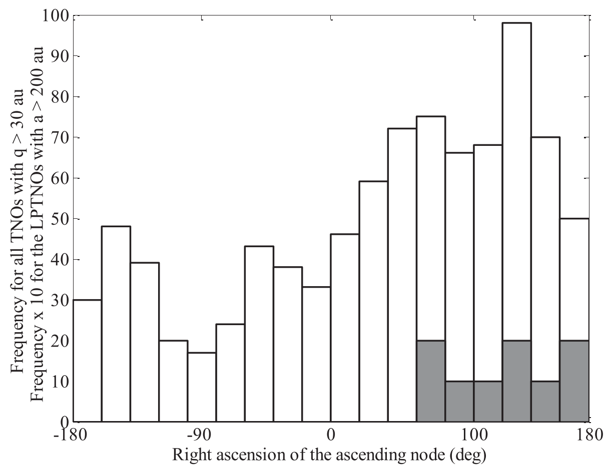

Figure 7. Frequency distribution of right ascension of the ascending node for all 896 TNOs with $q > 30$ au, which are not in resonance with Neptune and have $i > 1°$ (white bars). Similar to Fig. 6, this distribution also has a noticeable peak between 120° and 140° and significantly fewer TNOs have ω near $-90°$. This was shown to not be from a uniform distribution ($\alpha = 0.01$, p-value < 0.0001). The grey bars show 10 times the frequency of Ω for the nine LPTNOs with $a > 200$ au. They have a mean Ω of 122°.

listed in Table 1. Both distributions show a disproportionately large number of TNOs have an Ω of approximately 120°–140°.

However, Fig. 6 includes TNOs that could be in resonance with Neptune and bias the data. To account for this, we eliminated the 591 TNOs in Table 2 that might be in resonance with Neptune as we did when analysing ω. In the case of Ω, we also excluded orbits with very low inclinations. If $i = 0°$, Ω is undefined. If i is very close to 0°, Ω is almost undefined and is very sensitive to small perturbations. For these reasons, Ω is somewhat irrelevant for orbits that are close to the plane of the ecliptic. We therefore decided to exclude orbits with $i < 1°$. After eliminating all of these TNOs that could bias the data, there were still 896 TNOs beyond 30 au. A histogram of Ω for these orbits is shown in Fig. 7 (white bars). Similar to Fig. 6, many TNOs have Ω between 120° and

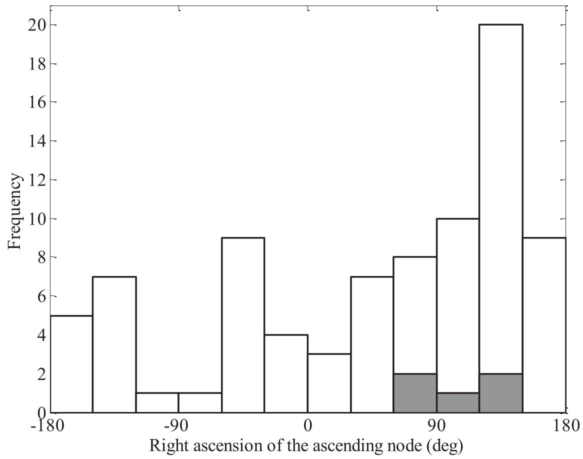

Figure 8. Frequency distribution of right ascension of the ascending node for all 84 TNOs with $q > 44$ au, which are not in resonance with Neptune and have $i > 1°$ (white bars). Similar to Figs 6 and 7, there is a peak between 120° and 150°. A K–S test was used to compare this histogram with those in Figs 6 and 7. In both cases, no difference was found ($\alpha = 0.01$, p-values = 0.09 and 0.21, respectively). The grey bars show the distribution of Ω for the five LPTNOs with $q > 44$ au. No statistical difference was found between this distribution and the 84 TNOs with $q > 44$ au ($\alpha = 0.01$, p-value = 0.21).

140°, and surprisingly few have Ω between −120° and −60°. As before, the grey bars show 10 times the frequency distribution of Ω for the nine LPTNOs. Even after removing TNOs that might introduce bias, a chi-squared test showed that the distribution of Ω for the 896 TNOs is not random with a statistical confidence of over 0.9999 ($\alpha = 0.01$, p-value < 0.0001). It also appears the clustering of the LPTNOs (grey bars) is consistent with the general population of TNOs. However, this hypothesis was barely rejected by a statistical test, but this might be due to the small number of LPTNOs ($\alpha = 0.01$, p-value = 0.006).

Finally, just like the analysis of ω, we also investigated the frequency distribution of Ω for TNOs that never get close to Neptune's orbit, which we conservatively defined to be $q > 44$ au. There are 84 known TNOs in this range, which also have $i > 1°$ and are not in resonance with Neptune. The distribution of Ω for these TNOs is shown in Fig. 8 (white bars). This looks very similar to Figs 6 and 7. By far the most common value for Ω is between 120° and 150°. Almost one-fourth of the TNOs have Ω in this range. In contrast, there are only two TNOs in Fig. 8 with Ω between −120° and −60°. A K–S test was unable to reject the hypothesis that the white bars in Fig. 8 are statistically similar to Figs 6 and 7 ($\alpha = 0.01$, p-values = 0.09 and 0.21, respectively).

The grey bars in Fig. 8 show the distribution of Ω for the five LPTNOs with $q > 44$ au. Their average value for Ω is 112°, which is consistent with the distribution of Ω for the 84 TNOs shown with white bars. A K–S test confirmed this and was unable to reject the hypothesis that these two distributions came from the same continuous distribution ($\alpha = 0.01$, p-value = 0.21).

5 DISCUSSION

All of the data presented clearly indicate that neither ω nor Ω is uniformly distributed as would be expected after just a few Myr. This is true when considering all TNOs with $q > 30$ au, even after eliminating those that might be in resonance with Neptune or could introduce other biases. It is also true when considering TNOs that never come close to Neptune's orbit ($q > 44$ au) and for the LPTNOs with $a > 200$ au.

Trujillo & Sheppard (2014) postulated that a large, undiscovered planet, located around 250 au, has kept ω for the LPTNOs from drifting significantly over billions of years. Another study suggested that two or more undiscovered super planets are needed to constrain ω (de la Fuente & de la Fuente 2014). These two studies only considered the clustering of ω near 0° for TNOs with $a > 150$ au. They could not explain why there was not a similar grouping near $\omega = 180°$. They also were apparently unaware that Ω is clustered almost as tightly for LPTNOs. Although super planets beyond Neptune could keep both ω and Ω clustered for LPTNOs (Kinoshita & Nakai 2007), there is no explanation why Ω would be clustered initially. It is also highly doubtful that there are any super planets between 200 and 300 au because of the observed precession of ω on known planets in our Solar system (Iorio 2014). Therefore, the LPTNOs should have random orbital elements after just a few Myr (Jíková et al. 2015). They clearly are not randomly distributed for the LPTNOs or for any other group of TNOs investigated here, including those in the Kuiper belt. Therefore, a more likely explanation is that TNOs have been in their present orbits for less than a few Myr. This is consistent with one possibility presented by Jíková et al. (2015), who stated that the clustering of ω for Sedna-like TNOs might have 'happened relatively recently (less than few Myr ago)'.

The right ascension of the ascending node for TNOs beyond 30 au is clearly not distributed randomly. For every group of TNOs investigated, a disproportionately large number have Ω between 120° and 140°, and few have Ω near −90° (Figs 1b, and 6–8). This is plausible if many of the TNOs were recently affected by Neptune. We propose that all the TNOs were inside Neptune's orbit within the last few Myr. Then they began to migrate away from the Sun due to a non-gravitational force. As they approached 30 au, a majority of these TNOs were drawn close to Neptune's orbital path, resulting in similar orbital elements to the giant planet. The orbit of Neptune is almost circular with a very low inclination and a right ascension of the ascending node of 132°. This is very consistent with the most common value for Ω between 120° and 140° for TNOs with $q > 30$ au and also $q > 44$ au, shown in Figs 6–8. It is also very close to the average Ω of 122° for the LPTNOs. In fact, all of the LPTNOs have Ω close to 132°. We believe that this is because all of the LPTNOs were drawn close to Neptune's orbit, causing them to become more aligned with its orbital plane and resulting in a similar value of Ω. All these LPTNOs also passed close enough to Neptune to receive a large gravitational boost, sending them farther from the Sun. This explains why all TNOs with large values of a have Ω close to 132° (Fig. 1b). It is also hypothesized that after these TNOs passed Neptune many continued migrating away from the Sun, but their values for Ω remained fairly constant, resulting in the distributions shown in this paper.

The frequency distribution of ω is also not close to being randomly distributed for any group of TNOs investigated. In fact, for $q > 30$ au, the distribution of ω statistically matches a continuous function of two overlapping normal distributions with means of 0° and 180° (Fig. 4). This would be expected if something near the plane of the ecliptic recently affected their orbits. As suggested by Trujillo & Sheppard (2014), the Lidov–Kozai effect could have accomplished this. However, this would have happened during the formation of our Solar system, and as previously discussed there is not a good mechanism that would constrain ω and Ω for billions of years. Another possibility is an existing giant planet, such as Neptune, could have affected many of the TNOs in the recent past. If, as proposed, the TNOs migrated from inside Neptune's orbit in the last few Myr, many would have been perturbed by Neptune as they passed 30 au. This would result in the distribution of ω displayed in Figs 3 and 4. However, there would have been some TNOs that never came close to Neptune as they migrated past 30 au and were not affected by the giant planet. This could explain why ultrawide TNBs exist in the Kuiper belt. Perhaps these fragile formations did not get torn apart by strong gravitational perturbations because they never came close to Neptune as they migrated.

The frequency distribution of ω for TNOs with perihelion greater than 44 au is statistically similar to TNOs with $q > 30$ au. This distribution can also divided into two groups, those with ω closer to 0° and those with ω closer to 180°. However, for $q > 44$ au, the average values for ω are not 0° and 180°. They are −27° and 167°, which is approximately 25° less than the general population of TNOs beyond 30 au. It is not clear what could have caused ω to decrease. Initially, we believed this could be due to perturbations from the known giant planets. However, in their extended data fig. 2, Trujillo & Sheppard (2014) show ω for 2012 VP_{113} does not decrease due to the known planets. Instead, it increases with time, and it would take over 400 Myr for ω to increase by 335° (equivalent to ω decreasing by 25°). Given the different perturbations on each TNO, ω and Ω would be randomly distributed after this length of time. Another possibility is perhaps the same non-gravitational force that caused TNOs to migrate away from the Sun also perturbed ω causing it to decrease slightly for those TNOs that continued to migrate after passing Neptune. As a result, TNOs beyond 44 au have a slightly lower value of ω. In contrast, those TNOs with very little non-gravitational forces did not migrate far after passing Neptune, and ω was not perturbed, leaving these TNOs with ω close to 0° or 180°.

If the theory proposed here is accurate, it would not be unusual to have ω for all nine LPTNOs clustered near −19° (and none near 180°), provided these LPTNOs were perturbed by Neptune about the same time. If so, it would be reasonable for all of them to either be perturbed up out of the plane of the ecliptic, resulting in ω close to 0°, or down below the plane of the ecliptic (ω close to 180°). It would just depend upon the relative position of Neptune and the TNOs when they passed each other. If the nine LPTNOs passed Neptune about the same time, their positions relative to Neptune would likely have been similar, and so would their values of ω, either all close to 0° or all close to 180°. This could also explain why their inclinations are also similar. If all the LPTNOs came close to Neptune with a comparable relative position, it is reasonable that they were all given a similar gravitational boost resulting in roughly the same inclination.

Additional research needs to be conducted to determine what could have caused TNOs to migrate past Neptune. The Yarkovsky effect is a potential mechanism that could have created this perturbation (Lorenz & Spitale 2004). This is caused by unequal thermal emissions and has been shown to create very small, but constant accelerations on asteroids resulting in larger orbits (Bottke et al. 2001; Chesley et al. 2003). However, it is unknown if this force could have moved all the TNOs beyond Neptune's orbit, especially large TNOs and the LPTNOs like Sedna. There is also no current explanation why this force, or any other proposed force, would have only acted recently. Further investigation is also needed to explain two differences discovered for TNOs with $q > 44$ au. We found these TNOs are much more likely to have circular orbits than those with $q < 44$ au. Also, the distribution of ω in Fig. 5 shows two peaks, which are approximately 25° lower than the general population of TNOs shown in Figs 3–5.

6 CONCLUSIONS

The origin of TNOs is not well understood. A number of theories have been proposed to explain their orbits, but each has some significant problems. Theories for the origin of the Kuiper belt are either unable to explain how planetesimals coalesced so far from the Sun (Lemonick 2014) or they have difficultly explaining how ultrawide TNBs were not separated when they were dispersed during Neptune's migration (Margot 2002; Pettit et al. 2008; Parker et al. 2011). TNOs with very large orbits, like Sedna, are even more troubling. It is especially difficult to explain why these TNOs have ω clustered close to 0° (Morbidelli & Levison 2004; Schwamb 2014).

We propose a new theory for the origin of TNOs that answers all of these questions and also explains the non-random distributions of ω and Ω presented here. First, we postulate all the TNOs, including the LPTNOs, have been their current orbits for less than a few Myr. There is strong evidence that large planets beyond Neptune, that could constrain ω and Ω, do not exist (Iorio 2014). Without such planets, the LPTNOs should have developed a random distribution of these orbital elements in just a few Myr (Jíková et al. 2015). It is likely this would have happened even sooner for TNOs with $q > 30$ au because the perturbations affecting these orbits are larger than for the LPTNOs. All the data presented here show these orbital elements are not randomly distributed for LPTNOs or those in the Kuiper belt, including those with $q > 30$ au or $q > 44$ au. Therefore, the most logical conclusion is that TNOs were placed in their orbits within the last few Myr.

We also propose that all the TNOs were inside Neptune's orbit. Then they began to migrate away from the Sun, due to a non-gravitational force. As they approached 30 au, many TNOs were affected by Neptune and developed a similar orbit, with Ω close to 132°. Some TNOs passed very close to Neptune and were given a significant gravitational boost. This included all of the LPTNOs, which explains why they all have a large semimajor axis and eccentricity, and a right ascension of the ascending node close to 132°.

Of all the TNOs affected by Neptune, about half were flung up above the plane of the ecliptic, resulting in ω close to 0°. The others were pitched down below the plane, yielding an ω close to 180°. We propose that all of the LPTNOs have a similar ω because they approached Neptune within a small time frame, when their relative positions to the giant planet were comparable, resulting in similar values for ω (which by chance happened to be close to 0° and not 180°). This can also explain why the inclinations of these orbits are all within 22.7 ± 9.4°. Perhaps, some of the LPTNOs were even orbiting each other before passing Neptune.

There also would have been some TNOs that were not perturbed by Neptune. As these TNOs migrated past 30 au, they never came close to Neptune. We believe that these TNOs included the ultrawide TNBs. Because they did not interact closely with Neptune, these fragile formations were able to remain intact as they migrated away from the Sun.

As all of the TNOs migrated past Neptune's orbit, it is believed that many continued drifting farther away from the Sun and increased their perihelion distances. These TNOs, including the LPTNOs, presumably had more non-gravitational forces than the others. Because it is proposed that this happened relatively recently, these orbits have not been greatly affected by small perturbations from the giant planets. As a result, the distributions of ω and Ω have not changed significantly. This explains why these orbital elements are not randomly distributed today.

Additional research is still needed to explain what force could have caused TNOs to migrate away from the Sun. The Yarkovsky effect is one potential mechanism that might have caused this. However, it remains to be seen if this could have moved all the TNOs into their present position after passing Neptune. There is also no explanation why this force, or any other non-gravitational force, would only happen recently. It is also unknown if such a force could have also perturbed ω for TNOs with $q > 44$ au, resulting in values that are about 25° lower than the expected means of 0° and 180°. Finally, further research is also needed to discover why TNOs with larger perihelion distances are much more likely to have circular orbits.

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