Extreme trans-Neptunian objects and the Kozai mechanism: signalling the presence of trans-Plutonian planets

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ABSTRACT
The existence of an outer planet beyond Pluto has been a matter of debate for decades and the recent discovery of 2012 VP$_{113}$ has just revived the interest for this controversial topic. This Sedna-like object has the most distant perihelion of any known minor planet and the value of its argument of perihelion is close to 0$^\circ$. This property appears to be shared by almost all known asteroids with semimajor axis greater than 150 au and perihelion greater than 30 au (the extreme trans-Neptunian objects or ETNOs), and this fact has been interpreted as evidence for the existence of a super-Earth at 250 au. In this scenario, a population of stable asteroids may be shepherded by a distant, undiscovered planet larger than the Earth that keeps the value of their argument of perihelion librating around 0$^\circ$ as a result of the Kozai mechanism. Here, we study the visibility of these ETNOs and confirm that the observed excess of objects reaching perihelion near the ascending node cannot be explained in terms of any observational biases. This excess must be a true feature of this population and its possible origin is explored in the framework of the Kozai effect. The analysis of several possible scenarios strongly suggest that at least two trans-Plutonian planets must exist.

Key words: celestial mechanics – minor planets, asteroids: general – minor planets, asteroids: individual: 2012 VP$_{113}$ – planets and satellites: individual: Neptune.

1 INTRODUCTION
Are there any undiscovered planets left in the Solar system? The answer to this question is no and perhaps yes! If we are talking about planets as large as Jupiter or Saturn moving in nearly circular orbits with semimajor axes smaller than a few dozen thousand astronomical units, the answer is almost certainly negative (Luhman 2014). However, smaller planets orbiting the Sun well beyond Neptune may exist and still avoid detection by current all-sky surveys (see e.g. Sheppard et al. 2011). Nevertheless, the answer to the question is far from settled and the existence of an outer planet located beyond Pluto has received renewed attention in recent years (see e.g. Gomes, Matese & Lissauer 2006; Lykawka & Mukai 2008; Fernández 2011; Iorio 2011, 2012; Matese & Whitmire 2011). So far, the hunt for a massive trans-Plutonian planet has been fruitless.

The recent discovery of 2012 VP$_{113}$ (Sheppard & Trujillo 2014), a probable dwarf planet that orbits the Sun far beyond Pluto, has further revived the interest in this controversial subject. Trujillo & Sheppard (2014) have suggested that nearly 250 au from the Sun lies an undiscovered massive body, probably a super-Earth with up to 10 times the mass of our planet. This claim is based on circumstantial evidence linked to the discovery of 2012 VP$_{113}$ that has the most distant perihelion of any known object. The value of the argument of perihelion of this Sedna-like object is close to 0$^\circ$. This property appears to be shared by almost all known asteroids with semimajor axis greater than 150 au and perihelion greater than 30 au (the extreme trans-Neptunian objects or ETNOs), and this fact has been interpreted as evidence for the existence of a super-Earth at 250 au. In this scenario, a population of stable asteroids may be shepherded by a distant, undiscovered planet larger than the Earth that keeps the value of their argument of perihelion librating around 0$^\circ$ as a result of the Kozai mechanism. Here, we study the visibility of these ETNOs and confirm that the observed excess of objects reaching perihelion near the ascending node cannot be explained in terms of any observational biases. This excess must be a true feature of this population and its possible origin is explored in the framework of the Kozai effect. The analysis of several possible scenarios strongly suggest that at least two trans-Plutonian planets must exist.

Trujillo & Sheppard (2014) claim that the observed excess of objects reaching perihelion near the ascending node cannot be the result of observational bias. In this Letter, we study the visibility of extreme trans-Neptunian objects and the details of possible observational biases. Our analysis confirms the interpretation presented in Trujillo & Sheppard (2014) and uncovers a range of additional unexpected patterns in the distribution of the orbital parameters of the ETNOs. The overall visibility is studied in Section 2 using Monte Carlo techniques and an obvious intrinsic bias in declination is identified. The impact of the bias in declination is analysed in Section 3. The distribution in orbital parameter space of real objects is shown in Section 4. In Section 5, our findings are analysed within the context of the Kozai resonance. Results are discussed in Section 6 and conclusions are summarized in Section 7.
2 VISIBILITY OF TRANS-NEPTUNIAN OBJECTS: A MONTE CARLO APPROACH

Trujillo & Sheppard (2014) focused their discussion on asteroids with perihelion greater than 30 au and semimajor axis in the range 150–600 au. Here, we study the visibility of these ETNOs as seen from our planet. The actual distribution of the orbital elements of objects in this population is unknown. In the following, we will assume that the orbits of these objects are uniformly distributed in orbital parameter space. This is the most simple choice and, by comparing with real data, it allows the identification of observational biases and actual trends easily. Using a Monte Carlo approach, we create a synthetic population of ETNOs with semimajor axis, eccentricity, longitude of the ascending node, inclination, argument of perihelion, and perigee at declination, which supports our previous result (see Table 1, and any conclusions obtained from them will be statistically fragile.

3 THE IMPACT OF THE DECLINATION BIAS

So far, all known trans-Neptunian objects with $q > 30$ au had $|\delta| < 24^\circ$ at discovery which supports our previous result (see Table 1 and Fig. 2). But this intrinsic bias may induce secondary biases on the observed orbital elements. If we represent the frequency distribution in right ascension and the orbital parameters $a$, $e$, $i$, $\Omega$ and $\omega$ for test orbits with $|\delta| < 24^\circ$, we get Fig. 3. Out of an initially almost uniform distribution in $a$, $i$, $\Omega$, and $\omega$ (see Figs 2 and A1), we obtain biased distributions in all these four parameters. In contrast, the distributions in $a$ and $e$ are rather unaffected (other than scale factors) by the intrinsic bias in $\delta$. Therefore, most objects in this population should be discovered with semimajor axes near the low end of the distribution, eccentricities in the range 0.8–0.9, inclinations under 40\degree, longitude of the ascending node near 180\degree and argument of perihelion preferentially near 0\degree and 180\degree. Any deviation from these expected secondary biases induced by the intrinsic bias in declination will signal true characteristic features of this population. Therefore, we further confirm that the clustering in $\omega$ pointed out by Trujillo & Sheppard (2014) is real, not the result of observational bias. Unfortunately, the number of known objects is small (13), see Table 1 and any conclusions obtained from them will be statistically fragile.

4 DISTRIBUTION IN ORBITAL PARAMETER SPACE OF REAL OBJECTS

The distribution in orbital parameter space of the objects in Table 1 shows a number of puzzling features (see Fig. 3). In addi-
to the clustering of $\omega$ values around 0° (but not 180°) already documented by Trujillo & Sheppard (2014), we observe clustering around 20° in inclination and, perhaps, around 120° in longitude of the ascending node. The distributions in right ascension, semimajor axis and eccentricity of known objects appear to be compatible with the expectations. However, (90377) Sedna and 2007 TG$_{322}$ are very clear outliers in semimajor axis. Their presence may signal the existence of a very large population of similar objects, the inner Oort cloud (Brown, Trujillo & Rubincowitz 2004). The distribution in inclination is also particularly revealing. Such a clustering in inclination closely resembles the one observed in the inner edge of the main asteroid belt for the Hungaria family (see e.g. Milani et al. 2010). Consistently, some of these objects could be submitted to an approximate mean motion resonance with an unseen planet. In particular, the orbital elements of 82158 and 2002 GB$_{32}$ are very similar. On the other hand, asteroids 2003 HB$_{37}$, 2005 RH$_{52}$ and 2010 VZ$_{50}$ all have similar $a$, $e$ and $i$, and their mean longitudes, $\lambda$, differ by almost 120° (see Table A1). This feature reminds us of the Hildas, a dynamical family of asteroids trapped in a 3:2 mean motion resonance with Jupiter (see e.g. Brož & Vokrouhlický 2008). If the three objects are indeed trapped in a 3:2 resonance with an unseen perturber, it must be moving in an orbit with semimajor axis in the range 195–215 au. This automatically puts the other two objects, with semimajor axis close to 200 au, near the 1:1 resonance with the hypothetical planet. Their difference in $\lambda$ is also small (see Table A1), typical of Trojans or quasi-satellites. Almost the same can be said about 2003 SS$_{122}$ and 2007 VJ$_{305}$. The difference in $\lambda$ between these two pairs is nearly 180°. On the other hand, the clustering of $\omega$ values around 0° could be the result of a Kozai resonance (Kozai 1962). An argument of perihelion librating around 0° means that these objects reach perihelion at approximately the same time they cross the ecliptic from South to North (librating around 180° implies that the perihelion is close to the descending node). When the Kozai resonance occurs at low inclinations, the argument of perihelion librates around 0° or 180° (see e.g. Milani et al. 1989). At the Kozai resonance, the precession rate of its argument of perihelion is nearly zero. This resonance provides a temporary protection mechanism against close encounters with planets. An object locked in a Kozai resonance is in a metastable state, where it can remain for a relatively long amount of time before a close encounter with a planet drastically changes its orbit.

5 DIFFERENT KOZAI SCENARIOS

The most typical Kozai scenario is characterized by the presence of a primary (the Sun in our case), the perturbed body (a massless test particle, an asteroid), and a massive outer or inner perturber such as the ratio of semimajor axes (perturbed versus perturber) tending to zero (for an outer perturber) or infinity (for an inner perturber). In the case of an outer perturber, the critical inclination angle separating the circulation and libration regimes is $\sim$39°; for an inner perturber it is $\sim$63° (see e.g. Gallardo, Hugo & Pais 2012). Here, the libration occurs at $\omega = 90°$ and 270°. Under these circumstances, aphelion (for the outer perturber) or perihelion (for the inner perturber) always occur away from the orbital plane of the perturber. This lack of encounters greatly reduces or completely halts any diffusion in semimajor axis. A classical example of an object submitted to the Kozai effect induced by an outer perturber is the asteroid...
6 DISCUSSION

Our analysis of the trends observed in Fig. 3 suggests that a massive perturber may be present at nearly 200 au, in addition to the body proposed by Trujillo & Sheppard (2014). The hypothetical object at nearly 200 au could also be in near resonance (3:2) with the one at nearly 250 au (e.g. if one is at 202 au and the other at 265 au, it is almost exactly 3:2). Any unseen planets present in that region must affect the dynamics of TNOs and comets alike. In this scenario, the aphelia, $Q = a(1 + e)$, of TNOs and comets (moving in eccentric orbits) may serve as tracers of the architecture of the entire trans-Plutonian region. In particular, objects with $\omega \sim 0^\circ$ or $180^\circ$ can give us information on the possible presence of massive perturbers in the area because they only experience close encounters near perihelion or aphelion (if the assumed perturbers have their orbital planes close to the Fundamental Plane of the Solar system). Their perihelia are less useful because so far they are $< 100$ au. However, the presence of gaps in the distribution of aphelia may be a signature of perturbational effects due to unseen planets. Fig. 3 shows the distribution of aphelia for TNOs and comets with semimajor axis greater than 50 au. The top two panels show the entire sample. The two panels at the bottom show the distribution for objects with $\omega < 35^\circ$ or $\omega > 325^\circ$ or $\omega \in (145, 215)^\circ$. These objects have their nodes close to perihelion and aphelion and their distribution in aphelion shows an unusual feature in the range 200–260 au. The number of objects with nodes close to aphelion/perihelion is just four. The total number of objects with aphelion in that range is 18. Immediately outside that range, the number of objects is larger. Although we may think that the difference is significant, it is unreliable statistically speaking because it could be a random fluctuation due to small number statistics. However, a more quantitative approach suggests that the scarcity is indeed statistically significant. If 18 objects have been found in $\omega \in (0, 360)^\circ$, 4 within an interval of $140^\circ$, and assuming a uniform distribution, we expect 7 objects not 4. The difference is just 0.8σ. Here, we use the approximation given by Gehrels (1986) when $N < 21$: $\sigma \sim 1 + \sqrt{0.75 + N}$. But Fig. 3 indicates that, because of the bias, objects with $\omega$ close to $0^\circ$ or $180^\circ$ are nearly four times more likely to be identified than those with $\omega$ close to $90^\circ$ or $270^\circ$. So, instead of 7 objects we should have observed 14 but only 4 are found, a difference of $2\sigma$, that is marginally significant. Therefore, if they are not observed some mechanism must have removed them.

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Table 1. Equatorial coordinates, apparent magnitudes (with filter if known) at discovery time, absolute magnitude, and $\omega$ for the 13 objects discussed in this Letter. 02000.0 ecliptic and equinox. Source: MPC Database.

| Object       | $\alpha$ (h,m,s) | $\delta$ (°,′,″) | $m$ (mag) | $H$ (mag) | $\omega$ (°) |
|--------------|------------------|------------------|-----------|-----------|--------------|
| (82158) 2001 FP365 | 11:57:50.69      | +00:21:42.7    | 22.2 (R)  | 6.0       | 6.77         |
| (90377) Sedna   | 03:15:10.09      | +05:38:16.5    | 20.8 (R)  | 1.5       | 311.19       |
| (148209) 2000 CR105 | 09:14:02.39   | +19:05:58.7    | 22.5 (R)  | 6.3       | 317.09       |
| 2002 GB32      | 12:28:25.94      | -00:17:28.4    | 21.9 (R)  | 7.7       | 36.89        |
| 2003 HB37      | 13:00:30.58      | -06:43:05.4    | 23.1 (R)  | 7.4       | 10.64        |
| 2003 SS422     | 23:27:48.15      | -09:28:43.4    | 22.9 (R)  | 7.1       | 209.98       |
| 2004 VN112     | 02:08:41.12      | -04:33:02.1    | 22.7 (R)  | 6.4       | 327.23       |
| 2005 RH32      | 22:31:51.90      | +04:08:06.1    | 23.8 (g)  | 7.8       | 32.59        |
| 2007 TG422     | 03:11:29.90      | -00:40:26.9    | 22.2 (R)  | 6.2       | 285.84       |
| 2007 VJ305     | 00:29:31.74      | -00:45:45.0    | 22.4 (R)  | 6.6       | 338.53       |
| 2010 GB174     | 12:38:29:365     | +15:02:45.54   | 25.09 (g)| 6.5       | 347.53       |
| 2010 VZ98      | 02:08:43:575     | +08:06:50.90   | 20.3 (R)  | 5.0       | 313.80       |
| 2012 VP113     | 03:23:47:159     | +01:12:01:65   | 23.1 (R)  | 4.1       | 293.97       |

(3040) Kozai that is perturbed by Jupiter. Another possible Kozai scenario is found when the ratio of semimajor axes (perturbed versus perturber) is close to one. In that case, the libration occurs at $\omega = 0^\circ$ and $180^\circ$; therefore, the nodes are located at perihelion and at aphelion, i.e. away from the massive perturber (see e.g. Milani et al. 1989). Most studies of the Kozai mechanism assume that the perturber follows an almost circular orbit but the effect is also possible for eccentric orbits, creating a very rich dynamics (see e.g. Lithwick & Naoz 2011). Trujillo & Sheppard (2014) favour a scenario in which the perturber responsible for the possible Kozai libration experimented by 2012 VP113 has a semimajor axis close to 250 au. This puts 2012 VP113 near or within the co-orbital region of the hypothetical perturber, i.e. the Kozai scenario in which the ratio of semimajor axes is almost 1. The Kozai mechanism induces oscillations in both eccentricity and inclination (because for them $\sqrt{1 - e^2 \cos \iota} = \text{const}$) and the objects affected will exhibit clustering in both parameters. This is observed in Fig. 3 but the clustering in $e$ could be the result of observational bias (see above).

7 CONCLUSIONS

In this Letter, we have re-examined the clustering in $\omega$ found by Trujillo & Sheppard (2014) for ETNOs using a Monte Carlo approach. We confirm that their finding is not a statistical coincidence and it cannot be explained as a result of observational bias. Besides, (90377) Sedna and 2007 TG422 are very clear outliers in semimajor axis. We confirm that their presence may signal the existence of a very large population of similar objects. A number of additional trends have been identified here for the first time:

- Observing from the Earth, only ETNOs reaching perihelion at $|\delta| < 24^\circ$ are accessible.
- Besides clustering around $\omega = 0^\circ$, additional clustering in inclination around $20^\circ$ is observed.
- Asteroids 2003 HB37, 2005 RH32 and 2010 VZ98 all have similar orbits, and their mean longitudes differ by almost $120^\circ$. They may be trapped in a 3:2 resonance with an unseen perturber with semimajor axis in the range 195–215 au.
- The orbits of 82158 and 2002 GB32 are very similar. They could be co-orbital to the putative massive object at 195–215 au.
- The study of the distribution in aphelia of TNOs and comets shows a relative deficiency of objects with $\omega$ close to $0^\circ$ or
180° among those with aphelia in the range 200-260 au. The difference is only marginally significant (2σ), though. Gaps are observed at ~205 au and ~260 au.

We must stress that our results are based on small number statistics. However, the same trends are found for asteroids and comets, and the apparent gaps in the distribution of aphelia are very unlikely to be the result of Neptune’s perturbations or observational bias. Perturbations from trans-Plutonian objects of moderate planetary size may be detectable by the New Horizons spacecraft (Iorio 2013).

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Figure 4. Distribution of aphelia for TNOs and comets with semimajor axis greater than 50 au: all objects (top panels) and only those with ω < 35° or ω > 325° or ω ∈ (145, 215)° (bottom panels).

Figure 5. Centaurs, TNOs, ETNOs and comets in the (e, a) plane. The dark gray area represents the eccentricity/semimajor axis combination with periapsis between the perihelion and aphelion of Jupiter, the light gray area shows the equivalent parameter domain if Neptune is considered instead of Jupiter. The brown area corresponds to the (e, a) combination with apoapsis between 190 and 210 au and the orange area shows its counterpart for the range 250–280 au.
Figure A1. Frequency distributions for the orbital elements of test orbits in Fig. 1. Bin sizes are as in Fig. 3. Error bars are too small to be seen.

APPENDIX A: ADDITIONAL FIGURES AND TABLES
Table A1. Various orbital parameters ($\varpi = \Omega + \omega, \lambda = \varpi + M$) for the 13 objects discussed in this Letter (Epoch: 2456800.5, 2014-May-23 00:00:00.0 UT. J2000.0 ecliptic and equinox. Source: JPL Small-Body Database.)

| Object       | $a$ (au) | $e$   | $i$ (°) | $\Omega$ (°) | $\omega$ (°) | $\varpi$ (°) | $\lambda$ (°) |
|--------------|---------|-------|---------|-------------|-------------|-------------|-------------|
| (82158) 2001 FP_{185} | 220.7545067 | 0.84492276 | 30.77926 | 179.32889 | 6.76597 | 186.09486 | 187.24430 |
| (90377) Sedna | 532.2664228 | 0.85696250 | 11.92861 | 144.52976 | 311.18801 | 95.71777 | 93.91037 |
| (148209) 2000 CR_{105} | 229.9196589 | 0.80773939 | 22.70769 | 128.23495 | 317.09262 | 85.32757 | 90.37358 |
| 2002 GB_{32} | 209.4649254 | 0.83128842 | 14.18242 | 177.01044 | 36.88563 | 213.89607 | 213.92324 |
| 2003 HB_{37} | 161.1315216 | 0.76362930 | 15.49540 | 197.85952 | 10.63985 | 208.49937 | 209.44502 |
| 2003 SS_{122} | 197.4196450 | 0.80023290 | 16.80405 | 151.10109 | 209.98241 | 1.08350 | 1.72635 |
| 2004 VN_{112} | 333.5527773 | 0.85809672 | 25.52708 | 66.04930 | 327.23428 | 33.28358 | 33.55408 |
| 2005 RH_{52} | 152.6816879 | 0.74449569 | 20.46892 | 306.19829 | 32.59337 | 338.79166 | 340.86704 |
| 2007 TG_{422} | 531.9002265 | 0.93310126 | 18.57950 | 112.98155 | 285.83713 | 38.81868 | 39.06830 |
| 2007 VJ_{305} | 192.3878720 | 0.81702908 | 11.98914 | 24.38420 | 338.53140 | 2.91560 | 4.04033 |
| 2010 GB_{174} | 368.2345380 | 0.86809900 | 21.53344 | 130.59114 | 347.52989 | 118.12103 | 121.29941 |
| 2010 VZ_{98} | 156.4583186 | 0.78062638 | 4.30909 | 117.47040 | 313.79473 | 71.26513 | 68.78231 |
| 2012 VP_{113} | 264.9446814 | 0.69599853 | 24.01737 | 90.88555 | 293.97160 | 24.85715 | 27.78384 |