Binary stripping as a plausible origin of correlated pairs of extreme trans-Neptunian objects

C. de la Fuente Marcos • R. de la Fuente Marcos • S. J. Aarseth

Abstract
Asteroids that follow similar orbits may have a dynamical connection as their current paths could be the result of a past interaction with a massive perturber. The pair of extreme trans-Neptunian objects or ETNOs (474640) 2004 VN₁₁₂–2013 RF₉₈ exhibits peculiar relative orbital properties, including a difference in longitude of the ascending node of just 1°61 and 3°99 in inclination. In addition, their reflectance spectra are similar in the visible portion of the spectrum. The origin of these similarities remains unclear. Neglecting observational bias, viable scenarios that could explain this level of coincidence include fragmentation and binary dissociation. Here, we present results of extensive direct N-body simulations of close encounters between wide binary ETNOs and one trans-Plutonian planet. We find that wide binary ETNOs can dissociate during such interactions and the relative orbital properties of the resulting unbound couples match reasonably well those of several pairs of known ETNOs, including 474640–2013 RF₉₈. The possible presence of former binaries among the known ETNOs has strong implications for the interpretation of the observed anisotropies in the distributions of the directions of their orbital poles and perihelia.

Keywords
Oort Cloud · Kuiper belt · Celestial mechanics · Minor planets, asteroids: general · Minor planets, asteroids: individual: (474640) 2004 VN₁₁₂ · Minor planets, asteroids: individual: 2013 RF₉₈

1 Introduction
The commissioning of large telescopes with wide fields of view equipped with sizeable mosaics of detectors has led to uncovering the presence of a group of extraordinary asteroids whose orbits are larger than those of any other previously known trans-Neptunian object (TNO) and have perihelion distances well outside the range defined by highly-eccentric, already catalogued asteroids and comets. The first member of this fascinating dynamical class was found in 2000, (148209) 2000 CR₁₀₅, and its discovery was soon acknowledged as an important milestone in the study of the outer Solar System because its current path cannot be explained within the standard eight-planets-only Solar System paradigm (e.g. Gladman et al. 2002; Morbidelli and Levison 2004). Sometimes labelled as distant Kuiper belt or inner Oort Cloud objects, Trujillo and Sheppard (2014) called these asteroids extreme TNOs or ETNOs if their semi-major axis, a, is greater than 150 AU and their perihelion distance —q = a (1 − e), eccentricity, e— is greater than 30 AU.

The number of ETNOs included in the database of the Minor Planet Center (MPC) stands at 28 (as of 2017 August 29), but at least one additional candidate object has already been announced (V774104 by Sheppard et al. 2015). The orbits of the ETNOs do not fit within an eight-planets-only Solar System, but the presence of one or more yet-to-be-discovered planetary bodies orbiting the Sun well beyond Neptune may be able to explain most, if not all, of the unexpected orbital characteristics displayed by the known ETNOs (de la Fuente Marcos and de la Fuente Marcos 2014, 2016a, 2016b, 2016c; Trujillo and Sheppard 2014; de la Fuente Marcos et al. 2015, 2016; Gomes et al. 2015; Batygin

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and Brown 2016; Brown and Batygin 2016; Malhotra et al. 2016; Sheppard and Trujillo 2016; Millholland and Laughlin 2017). This scenario is often referred to as the trans-Plutonian planets paradigm. As the subject of the possible existence of planets beyond Pluto is far from new, the term trans-Plutonian planet has already been used in the past (see e.g. Seidelmann 1971; Brady 1972; Radzievskij et al. 1994; Kuz’Michev and Tomanov 2006; Lykawka and Mukai 2008); in order to clearly separate TNOs from such planets, hereafter we use trans-Plutonian planet(s) instead of trans-Neptunian planet(s) even if the latter is certainly more usual.

Perhaps the most popular variant of the trans-Plutonian planets paradigm is the so-called Planet Nine hypothesis (Batygin and Brown 2016; Brown and Batygin 2016) that predicts the existence of one \( \sim 10 \, M_{\oplus} \) planet at about \( a = 700 \, AU \) based on the analysis of the observed clustering in physical space of the perihelia and the positions of the orbital poles of seven ETNOs –Sedna, 148209, \( \ldots \) 2004 VN\(_{112}\), 2007 TG\(_{422}\), 2010 GB\(_{173}\), 2012 VP\(_{113}\) and 2013 RF\(_{98}\) – and subsequent analytical and numerical work. Such anisotropies are the by-products of primary clusterings in inclination, \( i \), longitude of the ascending node, \( \Omega \), and argument of perihelion, \( \omega \), as pointed out by de la Fuente Marcos and de la Fuente Marcos (2016c) and, in principle, cannot be attributed to a selection effect (e.g. de la Fuente Marcos and de la Fuente Marcos 2014). However, Shankman et al. (2017a) have claimed that the Planet Nine hypothesis cannot reproduce the overall level of orbital clustering displayed by the known ETNOs and Shankman et al. (2017b) have recently argued that any clustering present among the known ETNOs is probably more apparent than real.

The existence of groupings in \( \Omega \) and \( \omega \) is indicative of some external perturbation only if it can be assumed that there is no detection bias. On the one hand, absence of detection bias is advocated by Trujillo and Sheppard (2014), and by Batygin and Brown (2016), Brown and Batygin (2016) and Brown (2017), while Bannister et al. (2017), Lawler et al. (2017) and Shankman et al. (2017a, 2017b) argue that strong detection biases may actually exist. De la Fuente Marcos and de la Fuente Marcos (2014) showed that there is indeed an intrinsic bias in declination, \( \delta \), induced by our observing point on Earth; when observed at perihelion or very near it (see their fig. 2), most ETNOs will be discovered at \( |\delta| < 24^\circ \) no matter how complete and extensive the surveys are. This intrinsic detection bias affects the distribution of observed orbital elements (see their fig. 3); in particular, most discoveries should show low orbital inclinations, but this is not what is observed. At this point, the presence or absence of harmful detection biases in the current ETNO sample are both plausible hypotheses until proven otherwise, but investigating this subject is beyond the scope of this paper.

Recent observational work has shown that, among the known ETNOs, the pair 474640–2013 RF\(_{98}\) stands out in terms of both dynamical and spectroscopic properties, suggesting that these two objects may have had a common physical origin (de León et al. 2017). The hypothesis of the existence of a genetic link for this pair is reasonably well supported by the currently available evidence. If a chance alignment is discarded, viable scenarios that could lead to a pair of closely related minor bodies include fragmentation and binary dissociation. Preliminary calculations show that binary dissociation after an encounter with a trans-Plutonian planet at very large heliocentric distance might be able to explain the origin of this pair of ETNOs (de León et al. 2017). Here, we present the results of a large number of direct \( N \)-body simulations of close encounters between wide binary ETNOs and one trans-Plutonian planet aimed at providing a detailed account of the binary dissociation process and its outcome. The goal of this research is not estimating the odds of a binary stripping event happening at hundreds of astronomical units from the Sun for which we do not have enough data yet, but its plausibility; therefore, our numerical exploration is mostly a theoretical exercise with potentially interesting practical applications. This paper is organized as follows. Some relevant properties of the ETNO pair 474640–2013 RF\(_{98}\) are summarized in Sect. 2 that also delves into the context of this research. Our \( N \)-body methodology is briefly outlined in Sect. 3. Section 4 describes an extensive exploration of the disruption mechanism and the orbital properties of the resulting unbound couples. The transition from newly disrupted couple to ETNO pair is studied in Sect. 5. Results are discussed in Sect. 6 and conclusions summarized in Sect. 7.

## 2 The pair (474640) 2004 VN\(_{112}\)–2013 RF\(_{98}\): relevant data and context

The state of the art for the pair (474640) 2004 VN\(_{112}\)–2013 RF\(_{98}\) has been reviewed by de León et al. (2017). Within the standard eight-planets-only Solar System paradigm and after performing extensive numerical simulations, Sheppard and Trujillo (2016) have classified 474640 as a long-term stable, extreme detached object; this conclusion is consistent with results from an independent analysis carried out by Brown and Batygin.
(2016). As for the other member of the pair, Sheppard and Trujillo (2016) have classified 2013 RF$_{98}$ as an extreme scattered object after finding that it becomes dynamically unstable within the standard paradigm over 10 Myr time-scales as a result of the influence of Neptune. In contrast, within the Planet Nine hypothesis (Batygin and Brown 2016; Brown and Batygin 2016) both objects are assumed to be long-term stable although some incarnations of the Planet Nine hypothesis make this pair very unstable on time-scales of order of dozens of Myr, being eventually ejected from the Solar System (see fig. 2 in de la Fuente Marcos et al. 2016). The resonant secular dynamics beyond Neptune in the absence of any significant external perturbers has been systematically explored by Saillenfest et al. (2017); their analysis suggests that the criteria used to consider TNOs as detached from the planets must be revised.

Prior to 2016 September, the available orbital solutions for this pair of ETNOs gave an angular separation between the directions of their perihelia (those of the vector going from the Sun to the respective perihelion point) of 9.78, very similar to the one between the directions of their velocities at perihelion/aphelion (9.5); however, their orbital poles were much closer at 4.1 and they had similar aphelion distances (589 AU versus 577 AU) as well. Following Öpik (1971), minor bodies with both similar directions of the orbital poles and perihelia could be part of a group of common physical origin. In an attempt to explore this scenario, astrometry, photometry and visible spectroscopy of the two targets were obtained on 2016 September using the OSIRIS camera-spectrograph at the 10.4 m Gran Telescopio Canarias (GTC) telescope (de León et al. 2017).

2.1 Updated data and their impact

The results in de Leόn et al. (2017) show that the spectral slopes of 474640–2013 RF$_{98}$ are very close matches, similar to those of (148209) 2000 CR$_{105}$ and 2012 VP$_{113}$, and compatible with the ones of 2002 GB$_{32}$ and 2003 HB$_{57}$ (two other members of the ETNO category not linked to the Planet Nine hypothesis). However, they are very different from that of Sedna, which was discovered in 2003 by Brown et al. (2004a) and is often regarded as the key object of this dynamical class (sometimes these objects are called Sednoids). Such spectral differences suggest that Sedna and the other objects do not share the same region of origin (see e.g. Sheppard 2010). This robust observational evidence may be at odds with the Sednitos theory (Jílková et al. 2015) that argues that Sedna and the other ETNOs were captured from the planetesimal disk of another star early in the history of the Solar System. Sedna may also be a statistical outlier among the ETNOs in terms of some other orbital and physical parameters (de la Fuente Marcos and de la Fuente Marcos 2016c).

Thanks to the new GTC observations, the orbital solution of 2013 RF$_{98}$ was considerably improved (de Leόn et al. 2016). Using the new orbits in Table [1] the relative differences in (heliocentric) $a$, $e$, $i$, $\Omega$, $\omega$ and time of perihelion passage, $\tau_q$, are respectively 32.6 AU, 0.0465, 3.99, 1.61, 15.26 and 56 days; the associated angular separation between the directions of the perihelia of this pair of ETNOs is now 14.1 (14.1$\pm$0.7) and between the directions of their velocities at perihelion/aphelion is 14.1, but their orbital poles still remain at 4.1 (4.059$\pm$0.003) from each other. Having relatively well-aligned orbital poles is indicative of a nearly common direction of orbital angular momentum which is often linked to the products of the break-up of a parent body. For this type of analysis, it may be claimed that when considering objects as distant as the ETNOs, it is perhaps better to use orbital elements that do not vary on very short time-scales, i.e. barycentric instead of heliocentric ones (see e.g. de la Fuente Marcos and de la Fuente Marcos 2016b; Malhotra et al. 2016). However, the positions of orbital poles and perihelia of the ETNOs are fairly insensitive to the differences between heliocentric and barycentric coordinates (de la Fuente Marcos and de la Fuente Marcos 2016c) because these differences are very small (well under 1%) for the particular case of the angular elements as Table [1] shows.

At this point it may be argued that a genetic link for the pair of ETNOs 474640–2013 RF$_{98}$ is not sufficiently substantiated, that there is a strong observational bias to detecting objects with similar perihelia and poles if discovery surveys are conducted at a similar epoch. It is indeed true that the two ETNOs subject of this investigation have been discovered by the same telescope; however, the instrument was significantly upgraded between 2004 and 2013, and the detector was replaced. The system used in 2013 is not similar to the one used in 2004, and the two surveys were independent, with different pointing strategies (see sect. 2 in de Leόn et al. 2017). In addition and even if the ETNOs are currently discovered when they are near or at perihelion, their orbital periods are longer than a few thousand years and they spend several decades close to perihelion; therefore, no particularly strong bias towards small relative differences (a few months) in $\tau_q$ is expected. It may also be claimed that no metric is used to confirm that the orbits of the pair of ETNOs 474640–2013 RF$_{98}$ are dynamically similar. These metrics are customarily applied when defining asteroid family links within
the main asteroid belt (see e.g. Milani et al. 2014; Nesvorný et al. 2015), but these asteroid families are mostly collisional in origin while the pair studied here could be the result of tidal stripping induced during a planetary encounter. In any case, if such metrics are applied to the current sample of known ETNOs the values obtained are all well above the thresholds used to define asteroid families in the main belt.

2.2 Pole and perihelion separations: out of the ordinary or not?

Within the context of the standard eight-planets-only Solar System paradigm, the distributions of the orbital parameters of minor bodies following orbits similar to the ones of the ETNOs should be statistically compatible with those of an unperturbed asteroid population moving in heliocentric Keplerian orbits (particularly in the case of objects like Sedna or 2012 VP113). Assuming such an unperturbed scenario and using a model similar to the one described by de la Fuente Marcos and de la Fuente Marcos (2014), the probability of finding values of the angular separations of the pertinent directions as low as those of the pair of ETNOs 474640–2013 RF98p is computed using expressions that share of the probability is still less than 0.0019. Although the input distributions in Ω and ω are uniform in the interval (0, 360)°, the resulting output distributions — obtained after imposing the various constraints— used to compute the angular separations are very different from the input ones (see fig. 3 in de la Fuente Marcos and de la Fuente Marcos 2014).

In this analysis, the probabilities associated with perihelia and poles are not independent as the location of these points is computed using expressions that share one or more orbital parameters (de la Fuente Marcos and de la Fuente Marcos 2016c). Our Monte Carlo analysis shows that the probability of two objects having an angular separation between the directions of their perihelia < 15° is 0.030; a similar calculation performed to find the probability of having an orbital pole separation < 5° gives a value of 0.023. The incorrect assumption of treating them as independent would lead us to evaluate the probability of interest here as simply the product of probabilities (or less than 0.0007), which is wrong. In Batygin and Brown (2016), when studying the issue of clustered perihelia and orbital pole positions, it is assumed that the two measurements are statistically uncorrelated and the joint probability of observing both clustering in perihelion position and in pole orientation

|                | (474640) 2004 VN112 |               | (474640) 2004 VN112 |               | (474640) 2004 VN112 |               |
|----------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|
|                | heliocentric       | barycentric   | heliocentric       | barycentric   | heliocentric       | barycentric   |
| Semi-major axis, a (AU) | 316.4±1.0          | 327.3         | 349±11             | 364           |
| Eccentricity, e         | 0.8505±0.0005      | 0.8554        | 0.897±0.003        | 0.901         |
| Inclination, i (°)      | 25.58±0.0002       | 25.5479       | 25.572±0.003       | 25.538        |
| Longitude of the ascending node, Ω (°) | 65.9895±0.0003 | 66.0223       | 67.596±0.005       | 67.636        |
| Argument of perihelion, ω (°) | 327.061±0.007  | 326.990       | 311.8±0.6          | 311.7         |
| Mean anomaly, M (°)     | 0.478±0.002        | 0.456         | 0.404±0.004        | 0.379         |
| Time of perihelion passage, τq (JED) | 2455069±2 | 2455064       | 2455125±95         | 2455131       |
| Perihelion, q (AU)       | 47.321±0.004       | 47.322        | 36.09±0.03         | 36.10         |
| Aphelion, Q (AU)         | 586±2              | 607           | 662±20             | 692           |
| Absolute magnitude, H (mag) | 6.5                | 8.7           |                    |               |
concurrently is found multiplying the probabilities together.

A somewhat similar study, but focusing on the putative clustering of poles and perihelia of the orbits of long-period comets, was carried out by Bogart and Noerdlinger (1982). Their investigation was limited to the three elements that specify the spatial orientation of an orbit (i, Ω and ω); in contrast, our Monte Carlo approach includes all the orbital parameters. If we apply eq. (1b) in Bogart and Noerdlinger (1982) considering \( (N =) 28 \) random orbits, a separation in orbital plane normals \( (X =) 5^\circ \), and a separation in perihelion directions \( (Y =) 15^\circ \), we obtain an average number of pairs expected within those ranges of relevant angular separations of 0.061 or a probability of 0.00016. Therefore, finding one pair like 474640–2013 RF\(_98\) is unlikely assuming that the ETNOs constitute an unperturbed asteroid population, but we do not know whether this pair is a true outlier or the ETNOs are indeed a perturbed population.

The value obtained when we apply eq. (1b) in Bogart and Noerdlinger (1982) is lower than our own, which indicates that using the entire orbit and restricting the values of \( q \) plays a role, as the size and shape of the orbits were neglected in their work. However, it still conveys the same message, that the existence of the ETNO pair 474640–2013 RF\(_98\) is unlikely not compatible with an unperturbed scenario or chance. As the visible spectra of the members of the pair are also close matches, a putative common physical origin is likely. As of the time of writing, only Sedna, 474640 and 2013 RF\(_98\) have spectroscopic results published. Without compositional information it is not possible to argue for a common genetic origin, no matter how similar the orbits of the objects involved are. In this respect, the pair 474640–2013 RF\(_98\) is unique at the moment. Viable scenarios that could explain these results include fragmentation and binary dissociation. In both cases, the presence of an unseen massive perturber, i.e. a trans-Plutonian planet, may be required.

2.3 Fragmentation versus binary dissociation: where are the binaries?

Close encounters between minor bodies and planets can induce fragmentation (e.g. Scheeres et al. 2000; Sharma et al. 2006; Ortiz et al. 2012), but the minimum approach distance associated with such events (about 20 planetary radii, see e.g. Keane and Matsuyama 2015) is far shorter than the one required for binary dissociation in the case of wide binaries whose binding energies are rather small (Agnor and Hamilton 2006; Vokrouhlický et al. 2008; Parker and Kavelaars 2010). The simplest formation mechanism for dynamically-related asteroid pairs is binary disruption during planetary flybys, but it requires the presence of binary asteroids moving on planet crossing orbits (e.g. Jacobson 2016). How likely is this possibility in our case?

The existence of wide binaries among the asteroid populations orbiting beyond Neptune is a well-documented fact (e.g. Parker et al. 2011); the widest known binary is 2001 QW\(_{322}\) with a semi-major axis of 102,100 km (Petit et al. 2008; Parker et al. 2011). They have been found preferentially among the dynamically cold, classical TNOs, but they are present within the scattered TNO population as well. Dysnomia, the satellite of the dwarf planet Eris, revolves about its host with a semi-major axis of 37,400 km (Brown et al. 2005, 2006). The moon of (225088) 2007 OR\(_{10}\) may have a binary semi-major axis of 29,300 km (Kiss et al. 2017). The only known satellite of the dwarf planet Makemake has a binary semi-major axis of over 21,000 km (Parker et al. 2016). The satellite of 2004 PB\(_{10}\) has a binary semi-major axis of 10,400 km (Grundy et al. 2009).

All TNOs larger than about 1000 km are known to harbour one or more moons (Barr and Schwamb 2016; Kiss et al. 2017). Fraser et al. (2017a, 2017b) have found that the blue-coloured (spectral slope < 17\%), cold TNOs are predominantly in tenuously bound binaries and proposed that they were all born as binaries at ~38 AU. Previous studies had estimated that the binary fraction among the dynamically cold TNOs could be about 30\% (Grundy et al. 2011) and it might reach ~10\% for the dynamically excited populations (Noll et al. 2008). It is thought that 10\% to 20\% of all TNOs could host one or more gravitationally bound companions (Brown et al. 2006), but see the detailed discussion in Petit and Moussis (2004).

Binary ETNOs have not yet been discovered, but Sedna (Brown et al. 2004b) and 474640 (Fraser and Brown 2012) have been observed with the Hubble Space Telescope and no close companions have been reported yet. In addition, most ETNOs are perhaps too faint to be observed by adaptive optics on even the largest existing ground-based telescopes, although detection biases favour the discovery of wide binaries.

2.4 Summary: a reasonably sound scientific case

Although the hypothesis of production of dynamically coherent pairs of ETNOs by binary dissociation induced by close encounters with a massive planetary perturber is interesting in its own right, it may be argued that...

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[1]http://www2.lowell.edu/~grundy/tnbs/status.html
this scenario appears to be very unlikely, as it requires a number of concurrent, low-probability ingredients in order to make it work.

First, one may argue that the ETNO pair 474640–2013 RF$_{98}$ is just one out of many similar pairs of ETNOs. However, this statement is far from true. With 28 known ETNOs, we now have 378 different pairs. The pair studied in this work is one of only two with a separation between orbital poles $< 5^\circ$ and a gap between directions of perihelia $< 15^\circ$; its associated $p$-value is therefore equal to 0.00529. If 474640–2013 RF$_{98}$ is an ordinary pair of ETNOs (from the point of view of the orientations in space of the orbits of both components), the probability of observing another pair of ETNOs with relevant angular separations as small or smaller than those of this pair should be relatively large. In striking contrast, a low value of the probability is found that we interpret as strong evidence against 474640–2013 RF$_{98}$ being a regular pair of ETNOs. It can still be argued that the orbital elements of the ETNOs are affected by uncertainties that a simple computation of probabilities like the previous one cannot take into account; therefore, its results cannot be relied upon at all. Following the ideas discussed by e.g. Fisher (1935), Basu (1980) and Welch (1990), we have used the available data provided by Jet Propulsion Laboratory (JPL)'s Solar System Dynamics Group Small-Body Database (Giorgini 2011, 2015) to generate $10^7$ random pairs of virtual ETNOs and computed the angular separation between orbital poles, $\alpha_p$, and perihelia, $\alpha_q$, of each of them. The angles have been calculated as described by de la Fuente Marcos and de la Fuente Marcos (2016c). Regarding the computation of the individual random orbits and focusing e.g. on the inclination parameter, a new value has been found using the expression $i_r = (\bar{i}) + \sigma_i r_i$, where $\bar{i}$ is the inclination of the random orbit, $i_r$ is the mean value of the inclination of one of the real ETNOs, $\sigma_i$ is its associated standard deviation, and $r_i$ is a (pseudo) random number with normal distribution in the range $-1$ to $1$. The resulting distributions of possible relevant angular separations of the ETNOs are plotted in Fig. 1 the actual dispersion in the values of the observed angles for the ETNO pair 474640–2013 RF$_{98}$ is represented by vertical lines. From this analysis, the probability of finding a pair of ETNOs with values of $\alpha_p$ and $\alpha_q$ both below those of the pair 474640–2013 RF$_{98}$ (4°:1 and 1°:1, respectively) is 0.00449±0.00002 (average and standard deviation from 10 sets of experiments). This value is independent of any assumptions made regarding the distributions and ranges of the various orbital elements (as we did in Sect. 2.2) and it is far too small to make this pair of ETNOs representative of the typical behaviour, in terms of relative orbital orientation in space, of the pairs present in the sample of known ETNOs.

Second, it can be claimed that there are no scientific grounds to argue for the presence of an unknown perturber, massive enough to cause binary dissociations and orbiting the Sun at hundreds of astronomical units. On the one hand, any unknown planet located between the trans-Neptunian belt (see e.g. Fernández 1980; Jewitt and Luu 1993) and the Oort Cloud (see e.g. Oort 1950) must have a mass less than that of Saturn ($5.68319 \times 10^{26}$ kg or over 95 Earth masses) to have escaped detection by the all-sky WISE survey (Luhman 2014); on the other hand, Larsen et al. (2007) have shown that their Spacewatch results obtained within $10^\circ$ of the ecliptic exclude the presence of any Mars-sized objects out to 300 AU and Jupiter-sized planets out to 1,200 AU. While the WISE survey was all-sky, the Spacewatch project covered 8,000 square degrees, avoiding the regions towards the Galactic centre (the clouds of Sagittarius and their neighbourhood), but focusing on low inclinations. Lykawka and Mukai (2008) have suggested that a planetary body smaller than the Earth could be following an eccentric and inclined orbit between 100 and 200 AU from the Sun, and cause the so-called Kuiper Cliff (see e.g. Chiang and Brown 1999). Holman and Payne (2016a) studied the available astrometry of Pluto and other TNOs to conclude that the presence of a planet at 60–100 AU with a mass as low as 0.6–3 Earth masses —from their eq. (5)— could not be ruled out. Volk and Malhotra (2017) have found robust statistical evidence that the mean plane of the trans-Neptunian belt is warped in such a way that an inclined, low-mass (probably Mars-sized), unseen planet could be responsible for the warping. In any case and although it may have an apparent magnitude in excess of 18, the presence of such a perturber (up to a few Earth masses) has not been effectively rejected by past or present surveys, particularly if it moves in a moderately inclined orbit (above $10^\circ$) and/or close to the Galactic plane (see e.g. Larsen et al. 2007; Brown et al. 2015). The possible perturber considered in our work is more distant and more massive than the one thought to be sculpting the Kuiper Cliff, but its existence has not been ruled out by recent analyses carried out by e.g. Brown and Batygin (2016), Fienga et al. (2016), Holman and Payne (2016a, 2016b), Sheppard and Trujillo (2016), and Brown (2017). In addition, the study of exo-planetary systems shows that planets moving in very wide orbits indeed exist (see e.g. Bailey et al. 2014; Naud et al. 2014) and that most exo-planets have values of their masses below those of

[https://ssd.jpl.nasa.gov/sbdb.cgi]
Uranus and Neptune but above that of the Earth (see e.g. Howard et al. 2010; Malhotra 2015; Silburt et al. 2015).

Third, if the pair of ETNOs is indeed unusual and (at least) one yet-to-be-detected distant planetary-mass perturber goes around the Sun between the trans-Neptunian belt and the Oort Cloud, how a wide binary asteroid may have survived as a bound pair until the relatively recent past? The answer to this legitimate question is not an easy and straightforward one, mainly because we do not know yet the actual source or sources of this population. If the source of the ETNOs is in the Oort Cloud, it is unclear what is the binary fraction there because no binary comets have ever been observed, although some can be considered as contact-binary comets —see e.g. 8P/Tuttle that has a strongly bifurcated nucleus (Harmon et al. 2010) or 67P/Churyumov-Gerasimenko (Sierks et al. 2015); the same can be said about a source within the inner Oort Cloud (Hills 1981). An origin in the region of the Giant planets early in the history of the Solar System can be readily discarded because a loosely-bound pair could not possibly survive recurrent gravitational encounters with the Jovian planets. As pointed out above, a possible source for tenuously bound TNO binaries has been identified by Fraser et al. (2017a, 2017b) at ∼38 AU and one may speculate that a similar source may exist well beyond the trans-Neptunian belt. In any case, if planets can form at 125–750 AU from the Sun (Kenyon and Bromley 2015, 2016), it is difficult to argue that minor bodies (and perhaps binaries) cannot.

Fourth, the frequency of such encounters, assuming that the perturber (the trans-Plutonian planet) and the target (the wide binary asteroid) do exist, is also a matter of concern. The classical method of Öpik (1951) and Wetherill (1967) has been recently revisited by Jeong Ahn and Malhotra (2017). An application of this theory results in an average value of the collision probability per year and pair of objects of the order of 10⁻¹⁰. Considering the age of the Solar System, 4,500 Myr, and that the inner Oort Cloud may have millions of members (Hills 1981; Levison et al. 2001), the existence of a non-negligible number of pairs of present-day ETNOs resulting from the dissociation of wide binaries is entirely possible.

In conclusion, based on our probabilistic argument, it is rather difficult to argue that the ETNO pair 474640–2013 RF₉₈ is just a standard couple of ETNOs; this pair is a true outlier. The orientations of their orbits are simply too well correlated to be the result of chance alone. Having correlated orientations implies a level of dynamical coherence only attainable as a result of fragmentation processes or binary dissociation.

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**Fig. 1** Possible distributions (the bin size is 0.5°) of the angular separations between orbital poles, $\alpha_p$, and perihelia, $\alpha_q$, for the known ETNOs. These are the result of the analysis of $10^7$ random pairs of ETNOs with synthetic orbits based on the mean values and dispersions of the orbital elements of real ETNOs (see the text for details). The observed dispersion (1σ) of the values for the ETNO pair 474640–2013 RF₉₈ is represented by vertical lines; this is clearly not an ordinary pair of ETNOs.
Fission could be the result of fast rotation, internal processes, or tidal encounters with massive perturbers. There are no currently known candidate mechanisms able to induce fast rotation or spontaneous fragmentation of minor bodies at hundreds of astronomical units from the Sun. In addition, fragmentation via tidal encounters is far less probable than binary dissociation as the encounters must take place at a much closer range in the first case. Therefore, we arrive at our proposed scenario by discarding other options that, in principle, appear to be far less probable and much more speculative. But, within the trans-Plutonian planets paradigm and assuming that wide binaries are also present among the ETNO population, how are they affected by interactions with a planet?

3 Dissociation of wide binary ETNOs: an $N$-body approach

In order to study the dissociation of wide binary ETNOs during close encounters with hypothetical trans-Plutonian planets, we use direct $N$-body simulations performed with a modified version of a code written by Aarseth (2003) that implements the Hermite integration scheme described by Makino (1991) as a fourth-order method. The standard version of this code is publicly available from the IoA website\footnote{http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm} the version used in this research includes purpose-specific input/output modifications. The value of the dimensionless time-step factor $ETA$ was very conservative, leading to very low typical relative energy errors; the total relative error in the value of the energy at the end of our integrations was always $\leq 10^{-12}$ and often as low as $5 \times 10^{-14}$. The quality of the results obtained with this software applied to Solar System calculations has been positively and extensively assessed by de la Fuente Marcos and de la Fuente Marcos (2012); in particular, fig. 3 in de la Fuente Marcos and de la Fuente Marcos (2012) shows that the results of long-term integrations performed with the program used in this study are similar to those obtained with other, well-tested codes.

Following the analysis by de la Fuente Marcos et al. (2016), our physical model includes the perturbations by the Jovian planets (Jupiter to Neptune) and one trans-Plutonian planet. Initial positions and velocities of both known planets and ETNOs are based on the DE405 planetary orbital ephemerides (Standish 1998) referred to the barycentre of the Solar System and to the epoch JD TDB 2457800.5 (2017-February-16.0), which is the $t = 0$ instant in our calculations. Heliocentric and barycentric Keplerian orbital elements of the pair (474640) 2004 VN$_{112}$–2013 RF$_{98}$ (see Table\footnote{http://ssd.jpl.nasa.gov/?planet_pos}) were provided by JPL’s On-line Solar System Data Service\footnote{http://ssd.jpl.nasa.gov/ssdbs.cgi} (Giorgini et al. 1996). Orbital elements are transformed into barycentric initial positions and velocities as needed. Two types of numerical experiments have been performed using the same software and physical model.

The first one (Sect. 4) is designed to explore the binary dissociation process itself as wide binary ETNOs experience encounters with one trans-Plutonian planet. Binary destruction could be the result of the total energy of the system becoming greater than zero, but also of enlargement of the binary semi-major axis beyond one Hill radius with respect to the Sun or even a collision. Due to the large size and high eccentricity of the orbits of the ETNOs, in this work we focus on physically unbound systems (energy condition) but (binary semi-major axis) enlargement-driven dissociations are also identified. The second type (Sect. 5) applies integrations backwards in time (see also de León et al. 2017), beginning with the present-day orbits of the unbound pair 474640–2013 RF$_{98}$ (see Table\footnote{http://ssd.jpl.nasa.gov/?planet_pos}) to investigate what properties a perturber should have to induce the observed tilt between the orbital planes of these ETNOs (4:1) starting from the values characteristic of newly disrupted pairs found from the analysis of the first set of numerical experiments.

For those experiments involving binaries and in order to compute the test orbit of the centre of masses of the binary, we consider how the elements influence each other and their associated uncertainties, applying the implementation of the Monte Carlo using the Covariance Matrix (MCCM) method discussed by de la Fuente Marcos and de la Fuente Marcos (2015). The binary orbits studied here have initial parameters drawn from a nominal orbit adding random noise to each initial orbital element as described by the covariance matrix. The covariance matrices used here were provided by JPL’s Small-Body Database\footnote{http://ssd.jpl.nasa.gov/ssdbs.cgi} and the vector including the mean values of the orbital parameters at the given epoch is of the form $v = (e, q, \tau_q, \Omega, \omega, i)$. Suitable initial conditions for the trans-Plutonian planet included in the simulations that result in binary dissociation events (Sect. 4) were identified by performing a preliminary experiment to single out candidate solutions of perturbers that may pass close enough to the binary ($< 2$ AU) for an integrated time of 8,000 yr. The
minimum separations between binary and planet during the simulated close encounters resulting from this experiment are plotted in Fig. 2. The input ranges for the parameters of the perturber (orbital elements and mass) were obtained from the set of experiments discussed in Sect. 5.

4 From wide binary ETNO to the newly disrupted state

The numerical experiments described in this section include a binary that follows a heliocentric orbit consistent with that of the present-day ETNO (474640) 2004 VN$_{112}$ (see Table 1): the binary experiences a flyby with a planetary perturber at hundreds of astronomical units from the Sun. This is a somewhat arbitrary but reasonable choice because the main objective of this study is neither reconstructing in detail the past dynamical history of the pair of ETNOs 474640–2013 RF$_{98}$ nor making an exhaustive exploration of the dynamical pathways leading to present-day pairs of ETNOs, but showing the feasibility of the binary-planet interaction scenario as a source of related pairs of ETNOs.

The heliocentric orbit of the binary at the beginning of each experiment is computed using the MCCM method (see above). The masses of the binary components are assumed to be $2.1 \times 10^{19}$ kg for the primary and $1.0 \times 10^{18}$ kg for the secondary; these values are consistent with results obtained by Parker et al. (2011) and de León et al. (2017). The orbital elements of the binary are drawn from uniform distributions with ranges $a_b \in (10,000, 400,000)$ km, $e_b \in (0.1, 0.9)$ but imposing a starting value of the binary apocentre < 600,000 km to ensure initial stability, $i_b \in (0, 180)^\circ$, $\Omega_b \in (0, 360)^\circ$, and $\omega_b \in (0, 360)^\circ$. For computational convenience, the binaries are always started at apocentre. The initialization of the binary components is carried out as described in sect. 8.3 of Aarseth (2003).

The upper limit in $a_b$ is somewhat arbitrary as no binary ETNOs have been detected yet, but the widest binary TNOs have average separations in units of the radius of the primary of the system $\leq 1,000$, with 2001 QW$_{322}$ being an outlier at 2,200 (Petit et al. 2008). Although most separations are $\leq 600$, 2000 CF$_{105}$ (Noll et al. 2002; Parker et al. 2011), 2003 UN$_{284}$ (Millis and Clancy 2003; Parker et al. 2011) and 2005 EO$_{304}$ (Kern et al. 2006; Parker et al. 2011) have values close to or slightly above 1,000. All these objects are cubewanos. Within this context and assuming primaries with sizes in the range 300–400 km, a value of the binary semi-major axis under 400,000 km does not seem implausible.

Fig. 2. Orbital elements and mass of a sample of trans-Plutonian planets (TPPs) undergoing close encounters with a wide binary ETNO moving in an orbit compatible with that of (474640) 2004 VN$_{112}$. The x-axis shows the minimum separation between binary and planet during the simulated close encounter. The solution associated with the closest approach was further refined to perform the experiments whose results are reported in Sect. 4. The results of $10^6$ experiments are plotted.
The orbit of the perturber — $a = 399.61 \pm 0.06$ AU, $e = 0.307 \pm 0.002$, $i = 23.86 \pm 0.03^\circ$, $\Omega = 77.76 \pm 0.05^\circ$, $\omega = 35.06 \pm 0.05^\circ$, and true anomaly, $f = 19.07 \pm 0.07^\circ$ — is based on a refinement of the optimal candidate orbits resulting from the experiment plotted in Fig. 2. Its randomized mass is assumed to be in the range $2$–$20 M_\oplus$. With such orbit and range of masses, the value of the Hill radius of the perturber is in the range $3.49$–$7.52$ AU; relevant minimum separations between binary and perturber during close encounters are well below this range of values. The encounters take place at $327.5 \pm 0.9$ AU from the Sun. For each experiment, the orbit of the perturber is drawn from uniform distributions defined by the assumed ranges. In order to minimize the chances of a physical collision at the binary ETNO or a capture as satellite by the planet, we perform hundreds of thousands of short $(8000$ yr or nearly one orbital period of the perturber) eight-body simulations. The results of these short numerical experiments are fully consistent with those of longer ones $(24000$ yr, compare Figs. 3 and 4) for the relevant section of the relative orbital parameter space ($\Delta a > 10$ AU, see below); however, the overall fraction of unbound pairs increases by 1% when the time interval is tripled. This arbitrary choice for the duration $(24000$ yr) of this second set of control calculations has nothing to do with the existence of a time window of observability of the members of the pair after disruption. The sole purpose of this additional set of control calculations is gaining a better understanding of the border-line cases of binary dissociation, but these cases are not central to our study.

Figure 3 shows the differences between the values of the heliocentric orbital elements of the members of the initially bound binary at the end of the simulation for $500000$ experiments (differences for angular elements $\leq 180^\circ$). Pairs that are still bound (energy condition) at the end of the simulation are plotted in green, unbound couples in red if the total energy of the system is greater than zero or orange if the total energy condition) at the end of the simulation are plotted in blue for comparison. These pairs are the ones with the lowest values of the angular separation of the orbital poles of their components ($< 10^\circ$, de la Fuente Marcos and de la Fuente Marcos 2016c) and, therefore, the most probable by-products of the dynamical scenario under study here.

Out of $500000$ experiments, $22.3\%$ $(111307)$ produced a newly disrupted couple. Out of these unbound pairs, $87.9\%$ $(97851)$ were physically unbound systems, the remaining $12.1\%$ $(13456)$ experienced mutual orbit expansion beyond one Hill radius. The fraction of collisions and captures was $1.3\%$ $(6490)$. Nearly $1.3\%$ $(6427)$ of the experiments performed resulted in the hyperbolic ejection of at least one member of the pair, i.e. one or both components escaped from the Solar System to become interstellar minor bodies.

Out of the full pairs that left the Solar System, about $29.6\%$ $(1869)$ were still bound as binaries. Over $0.03\%$ of the experiments produced a disrupted couple with just one member being ejected from the Solar System. Figures 3 and 4 show that the fraction of disrupted couples with total energy of the system still negative decreases significantly over time (from $12.1\%$ to $5\%$ as they become physically unbound) and also that the most sensitive parameter regarding time evolution is $\tau_q$ (compare top panels). The fraction of unbound pairs with $\Delta a > 10$ AU and difference in $\tau_q$ shorter than one year becomes practically negligible after $24000$ yr of evolution; i.e. if $\Delta \tau_q$ is very short (weeks to months), the unbound pair must be dynamically very young or the short $\Delta \tau_q$ must be due to chance.

Our results show that, within the scenario discussed here, wide binary ETNOs can fully dissociate during close encounters with hypothetical trans-Plutonian planets and most binaries are destroyed when the system becomes physically unbound. However, the majority of unbound pairs with $\Delta a < 10$ AU are borderline cases where the total energy of the binary system is positive, but only by a slight margin. The total energy of these systems may become marginally negative at a later time. The fraction of these systems is somewhat reduced in longer integrations as they become more tightly bound (or the components recede further from each other) over time (see Fig. 4). Unbound pairs with larger $\Delta a$ are bona fide newly disrupted couples; these are the ones of interest here and their relative numbers do not change significantly between Figs. 3 and 4 ($1.8\%$ versus $2.2\%$).

Figure 5 shows the frequency distribution of the initial orbital elements of the binaries that became unbound pairs. Wider pairs ($a_n > 0.0015$ AU, see Fig. 5 top panel) are far more likely to suffer dissociation (about 5 times) than tighter ones, but the role of the eccentricity, inclination, longitude of the ascending node, and argument of pericentre of the binary on the overall disruption results is minor (see Fig. 5 second panel and below). More eccentric binaries are a bit more...

\footnote{For the numerical experiments lasting $24000$ yr, Fig. 4 23.3\% (116561) resulted in binary dissociation, out of these, 96.0\% (110752) had positive relative energy; the fraction of ejections/collisions/captures was 1.3\%.}
Differences between the values of the heliocentric orbital elements of the members of the initially bound binary at the end of the simulation (8 000 yr). Bound pairs are plotted in green, unbound couples in red (energy condition) and orange (separation condition); the blue points show the actual values for the pairs of ETNOs (474640) 2004 VN112–2013 RF98 (Δa = 32.6 AU), 2002 GB32–2003 HB57 (Δa = 51.9 AU), (82158) 2001 FP155–2013 UH15 (Δa = 54.8 AU), and (148209) 2000 CR105–2010 GB174 (Δa = 143.1 AU). These pairs have angular separations of the orbital poles < 10°. The results of 500 000 experiments are plotted, excluding hyperbolic ejections and collisions/captures.

Fig. 3 Differences between the values of the heliocentric orbital elements of the members of the initially bound binary at the end of the simulation (8 000 yr). Bound pairs are plotted in green, unbound couples in red (energy condition) and orange (separation condition); the blue points show the actual values for the pairs of ETNOs (474640) 2004 VN112–2013 RF98 (Δa = 32.6 AU), 2002 GB32–2003 HB57 (Δa = 51.9 AU), (82158) 2001 FP155–2013 UH15 (Δa = 54.8 AU), and (148209) 2000 CR105–2010 GB174 (Δa = 143.1 AU). These pairs have angular separations of the orbital poles < 10°. The results of 500 000 experiments are plotted, excluding hyperbolic ejections and collisions/captures.

vulnerable to disruption, as are those with \(i_b > 40°\); binaries with \(\Omega_b\) close to 140° or 320° appear to a certain extent less prone to become disrupted couples. If \(a_b \geq 0.002\) AU, the fraction of binary disruptions is close to 50%. For \(a_b \sim 0.0015\) AU, nearly 25% of the initially bound binaries are disrupted. If we focus on binaries with \(a_b < 150\ 000\) km (or 0.001 AU), the fraction of unbound couples at the end of the simulation is < 15%. For this tighter group, the role of the binary orbital elements (other than \(a_b\)) on the disruption outcome is in every way negligible.

Figure 6, top panel, shows that most binary dissociation events are the result of close encounters at minimum approach distances smaller than about 0.25 AU. For encounters under 1 AU over 20% of the binaries become unbound pairs; however, nearly 75% of the binaries reaching separations from the perturber below 0.1 AU are disrupted. This is to be expected because if the planetocentric trajectory of the binary is hyperbolic, the deeper the encounter, the stronger its effects on the orbital parameters of the binary. For a given minimum approach distance, the binary destruction fraction depends on the value of \(a_b\). However, the outcome of close encounters under 0.01 AU is virtually insensitive to the value of the binary semi-major axis. If we consider binaries with \(a_b < 150\ 000\) km that approach the perturber inside 0.01 AU, nearly 75% of them are disrupted; in stark contrast, just about 6% of them become unbound if the encounter is below 1 AU. Nearly 10% of the unbound pairs (11 442 out of 111 307) had \(a_b < 150\ 000\) km. In general, most unbound pairs with \(\Delta a > 10\) AU are the result of close encounters inside 0.1 AU that is about 25 times the value of the maximum initial binary apocentre (600 000 km).

Both Figs. 3 and 4 show that newly disrupted couples may have relatively different values of the semi-major axis and eccentricity but very similar values of the orbital inclination, longitude of the ascending node, and argument of perihelion parameters. The difference in time of perihelion passage can range from weeks to centuries. This implies that unbound pairs are expected to move initially along paths featuring similar directions of the perihelia, orbital poles, and perihelion/aphelion velocities. Figure 8 shows the differences between the values of the orbital parameters, but in the case of the semi-major axes, the actual values for many of the unbound pairs are very different from that of the parent binary. Figure 7, bottom panel, shows that most disrupted pairs are scattered inwards. The orbital inclination tends to increase (Fig. 7, third panel from bottom) and the value of the argument of perihelion decreases (Fig. 7, second panel). As for the statistical significance of these results, let us consider as reference an isotropic distribution for the ratio of values
Fig. 4  As Fig. 3 but for integrations lasting 24,000 yr instead of 8,000 yr. The results of 500,000 experiments are plotted, excluding hyperbolic ejections and collisions/captures.

Fig. 5  Frequency distribution of the initial orbital elements of the binaries that became disrupted couples after interacting with a trans-Plutonian planet (experiments as in Fig. 3). The number of bins is $2^{n/3}$ where $n = 111,307$. The dashed line shows the results of an equivalent uniform distribution. In this and subsequent histogram figures, the cumulative frequency is plotted as a black curve.
Fig. 6 Frequency distribution of the separation during close encounter of the binaries analysed in Fig. 5 (top panel). Frequency distribution of the difference in heliocentric semi-major axes of the unbound couples (ejections/collisions/captures excluded) at the end of the simulation for encounters under 1 AU (second to top panel), 0.5 AU (second to bottom panel), and 0.1 AU (bottom panel). The number of bins is 2 $n^{1/3}$, where $n$ is equal to 111,307, 106,744, 105,794 and 16,489, respectively.

The results obtained in the previous section show that newly disrupted couples resulting from binary dissociation events may have relatively different values of $a$ and $e$ but very similar values of $i$, $\Omega$ and $\omega$; therefore, the (i.e. ratios > 1 and < 1 are equally probable), where $\sigma = \sqrt{n}/2$ is the standard deviation of binomial statistics. The semi-major axes of the unbound couples tend to be smaller than that of the parent binary; there is a $44\sigma$ departure from an isotropic distribution in $a_i/a_0$. The resulting eccentricities tend to be smaller at the 9$\sigma$ level. However, the orbital inclinations of the members of the unbound pair do not show any statistically significant preference as they tend to increase at the 1$\sigma$ level. In stark contrast, the longitude of the ascending node increases at the 90$\sigma$ level, the argument of perihelion decreases at the 185$\sigma$ level, and the time of perihelion passage increases at the 164$\sigma$ level. Figure 7 shows that closer encounters tend to increase significantly the dispersion in the relative values of the orbital parameters; this trend seems to ease for very close encounters (< 0.1 AU), but the number of points is too low to arrive at solid conclusions.

Figure 8 shows the ratio between the values of the orbital elements of the members of the unbound pair at the end of the simulation and the initial ones as a function of the mass of the perturbing trans-Plutonian planet. The dispersion increases with the mass of the perturber. The effect of the mass of the perturber is unclear from Fig. 3 but it is important as we can see in Fig. 6. The dashed line shows the results of the effectiveness of the binary dissociation process when the effect of the mass of the perturber is negligible, in sharp contrast the actual distribution is far from uniform. Heavier perturbers are more effective at disrupting binaries, all the other parameters being nearly the same. The mass of the putative perturber that triggered the dissociation of the original binary may have been $> 10 M_{\oplus}$ (see Fig. 9).

Regarding the similarity in absolute terms between the parameters of the unbound pairs and those of the pair of ETNOs 474640–2013 RF98, only a few unbound couples have values of their semi-major axes similar (±50 AU) to those of the ETNO pair of interest here (see Table 1). This suggests that, in this case, the hypothetical parent binary may have followed an orbit somewhat exterior to those of the current pair of ETNOs. The orbit would have been more eccentric and perhaps slightly less inclined.

5 From the newly disrupted state to ETNO pair

The results obtained in the previous section show that newly disrupted couples resulting from binary dissociation events may have relatively different values of $a$ and $e$ but very similar values of $i$, $\Omega$ and $\omega$; therefore, the
Fig. 7  Ratio between the values of the orbital elements of the members of the unbound pair at the end of the simulation and the initial ones as a function of the separation during close encounter of the binaries (data as in Figs. 5 and 6, top panel, but excluding hyperbolic ejections and collisions/captures, 213,488 unbound ETNOs).

Fig. 8  Same as Fig. 7 but as a function of the mass of the trans-Plutonian planet.

Fig. 9  Frequency distribution of the mass of the perturber ($M_{TPP}$) responsible for the binary dissociation events. The dashed line shows the results of a uniform distribution. Data as in Fig. 6 top panel.
unbound pairs move initially along paths featuring similar directions of the orbital poles. Figure 10, top panel, shows the frequency distribution of the angular separation between the orbital poles of the unbound pairs at the end of the simulation; focusing on the 8670 unbound pairs with $\Delta a > 10$ AU (Fig. 10, bottom panel) does not change the frequency distribution too significantly, but there is indeed a trend to have larger polar separations.

The vast majority of newly disrupted couples start their dynamical lives with their orbital planes mutually tilted by an angle $< 1^\circ$. Finding newly disrupted couples with their orbital planes mutually tilted by a wider angle is certainly not impossible (Fig. 10, bottom panel), but it is indeed far less probable. Although the angular separations between the orbital poles of known ETNO pairs that might have been former binaries are small, none of them are below $1^\circ$ (see sect. 2 and fig. 2 in de la Fuente Marcos and de la Fuente Marcos 2016c); therefore and in order to explain the observational values, we must assume that the initially very small separation increases over time due to some external force. The natural choice for the source of such secular perturbation is the planet responsible for the binary dissociation event if the unbound pair experiences additional, more distant encounters with it over an extended period of time. In this scenario, recurrent close approaches take place at regular intervals so we can speak of resonant returns (Milani et al. 1999). Unfortunately, the perturbations from the very planet that caused the disruption of the binary also make the determination of the past dynamical history of present-day unbound couples quite difficult.

In order to explore further the feasibility of this hypothesis, the numerical experiments carried out in this section do not involve binaries but the actual ETNOs whose orbits are integrated backwards in time to study the evolution of the value of the angular separation between their orbital poles when the ETNOs are subjected to the action of a sample of perturbers. This approach aims at finding the most probable orbital parameters of a hypothetical planet able to tilt the orbital plane of the pair (474640) 2004 VN$_{112}$–2013 RF$_{98}$ from an initial angular separation close to zero at dissociation (see Fig. 11) to the current value of slightly over $4^\circ$. Such experiments involve $N$-body integrations backwards in time under the influence of an unseen perturber with varying orbital and physical parameters (assuming uniform distributions) so the relevant volume of parameter space is reasonably well sampled. For these experiments, the ranges of the parameters of the perturber are the ones in Fig. 11 and coincide with those in Fig. 2; the input orbits of the ETNO pair are

![Fig. 10](image-url)
based on the orbital elements in Table 1 and computed using the MCCM method (see above) as in the case of the binaries in Sect. 4. The software applied and the physical model assumed are also the same.

Figure 11 shows the results of 11,000 eight-body experiments where the orbits of the pair of ETNOs were integrated backwards in time for 8 Myr, subjected to the perturbation of a sample of trans-Plutonian planets. The impact of the properties of the perturber on the final value of the angular separation between the orbital poles of the pair shows some interesting trends. Perturbers with large values of the semi-major axis are somewhat disfavoured (see Fig. 11 bottom panel); the best value could be \( \sim 350 \) AU. Eccentricities around 0.2–0.4 are preferred as well as orbital inclinations above 20° (see Fig. 11 third and second last panels). The longitude of the ascending node of the orbit of the perturber must be in the neighbourhood of 70° (see Fig. 11 third panel) and the value of its argument of perihelion is left relatively unconstrained (see Fig. 11 second panel) although values in the neighbourhood of 60° and 280° seem to be preferred. The mass of an effective putative perturber must be \( > 9 M_{\oplus} \) (see Fig. 11 top panel) which is consistent with the results in Sect. 4. Some representative examples of individual experiments are shown in Fig. 12 (see also fig. 5 in de León et al. 2017).

The results of this set of experiments are only slightly different from those in Fig. 2; the largest differences appear in the case of the values of eccentricity and argument of perihelion. However, being able to increase the tilt between two given orbital planes and capable of triggering binary dissociation are not necessarily concurrent outcomes for a given set of initial conditions. Although the process of disruption of wide ETNO binaries can only be effectively accomplished during binary-planet encounters at close range (under about 0.25 AU, see above), smooth and progressive increase of the relative tilt does not require such level of proximity. An unbound pair resulting from a close encounter may be inserted in new orbits that preclude further approaches at close range to the planetary body that triggered the dissociation of the parent binary. In sharp contrast, our two sets of experiments use as input data consistent orbits (with that of 474640) for both binaries and unbound pairs.

6 Discussion

The topic of the destruction of binaries by scattering encounters with a planet in the outer Solar System has been studied previously by Parker and Kavelaars (2010). As ours, their work focuses on the end states
of binary asteroids after binary-planet encounters, but they simulate the effects of interactions between binary TNOs and Neptune. They used the MERCURY 6 N-body code (Chambers 1999) to integrate a population of 15,000 particles for 1 Myr, performing 7,500 integrations of the binary-TNO-Neptune interactions; their binaries have binary semi-major axes uniformly distributed in the range 2000–120,000 km, but the other binary orbital parameters are similar to those in our experiments. In our longer integrations (24,000 yr), nearly 95% of the binary dissociations correspond to unbound systems. Almost 99% of the binary dissociations observed in their calculations were due to the binary semi-major axis being enlarged to more than one Hill radius, not because the total energy of the system became greater than zero as in our case. Such a sharp difference could be the result of using orbits of very different sizes; our ETNOs have a ~328 AU, their TNOs have a in the range 20–34 AU. The fraction of collisions in both studies is about the same. Up to 80% of binaries with binary semi-major axis in units of the Hill radius ~0.1 are disrupted in their simulations. In spite of the different scenarios implied, our results are somewhat consistent with theirs; we find that binaries with a_H in units of the Hill radius > 0.14 are preferentially disrupted, although our disruption rates are lower than theirs probably because our integrations are much shorter. They found that the probability of binary dissociation depends weakly (< 10%) on the initial eccentricity and inclination of the binary pair which is consistent with our own findings, but we also find a weak dependency on the value of the mutual longitude of the ascending node and argument of perihelion (see Fig. 1).

The results in Sect. 4 are based on a single representative orbit of the putative perturber; this orbit is only marginally compatible with the orbital solution favoured in Sect. 5. But these results, how do they compare with those from a perturber moving in other orbits? Figure 13 is similar to Fig. 3 but now the orbital parameters of the perturber are more consistent with the results in Sect. 5 (see Fig. 11). The orbit of the perturber —a = 478.92 ± 0.03 AU, e = 0.338 ± 0.003, i = 26.46 ± 0.04°, Ω = 65.98 ± 0.03°, ω = 273.85 ± 0.013°, and f = 148.41 ± 0.06°— has been obtained after performing a Monte Carlo-powered search analogous to the one producing the orbit of the perturber used in Sect. 4; its mass is assumed to be in the range 2–20 M_Earth. Each numerical experiment runs for 10,500 yr or nearly one orbital period of the perturber. The encounters now take place at about 474 AU from the Sun. For identical target binary population, this perturber is significantly less efficient in triggering binary dissociations; only 1.9% of the binaries were disrupted and out of them 91.2% had positive relative energy. The relative orbital elements of the resulting unbound pairs also exhibit distinctive features; in particular, unbound pairs with differences in their times of perihelion passage below 1 yr are very scarce in the new simulations.

We also tested a more inclined orbit for the perturber —a = 462.43 ± 0.03 AU, e = 0.1489 ± 0.0009, i = 51.08 ± 0.02°, Ω = 173.36 ± 0.04°, ω = 78.26 ± 0.03°, and f = 75.24 ± 0.04°— with each numerical experiment running for 10,000 yr or nearly one orbital period of the perturber and encounters taking place at about 417 AU from the Sun. This particular perturber is precisely the one producing the smallest separation in Fig. 2. This set of calculations yielded a fraction of destroyed binaries of nearly 9%; over 88% of them had positive relative energy. An additional set of experiments —a = 384.15 ± 0.02 AU, e = 0.528 ± 0.002, i = 27.31 ± 0.03°, Ω = 100.52 ± 0.03°, ω = 119.91 ± 0.03°, and f = 67.27 ± 0.02°— running for 8,000 yr and producing encounters at about 209 AU from the Sun gave a binary disruption rate of 9.2% with 99.7% of the disrupted binaries having positive relative energy at the end of the simulation. All these variations are the result of the different geometry associated with the close encounters. The new perturbers require closer encounters to induce effects comparable to those of the original one because the relative velocity during approaches at close range is now higher. In general, fast binary-planet encounters are only disruptive if very deep; slower encounters can be effective even if they are relatively shallow, but slow encounters are more sensitive to initial conditions.

It may be argued that there are a host of other processes able to dissociate a binary system such as small impacts or solar tides; on the other hand, dynamically-related pairs of asteroids can be the result of fragmentation at perihelion, strong mean motion or secular resonances as well. Binary dissociation induced by asteroidal impacts requires a significant amount of debris to make it a viable mechanism; it is unclear whether the outer Solar System between the trans-Neptunian belt and the Oort Cloud has the required amount of mass orbiting at the right inclination. Solar tides are negligible unless the binary asteroid has a perihelion within a few tenths of an astronomical unit (see e.g. Scheeres 2006). Fragmentation at perihelion is possible, but the absence of an obvious triggering mechanism makes it unlikely.

The possible presence of former binaries among the known ETNOs has strong implications for the interpretation of the observed anisotropies in the distributions of the directions of their orbital poles and perihelia. Figures 3 and 4 suggest that a non-negligible fraction
As Fig. 3 but for a different perturber (see the text for details). The results of 500,000 experiments are plotted.

Fig. 13

(Perhaps higher than 25%) of the known ETNOs might have had its origin in dissociated binaries. This implies that their current orbital elements may correlate not just because of the secular perturbation of a putative trans-Plutonian planet but as a result of a pre-existing dynamical link as well. This scenario also adds weight to the characterization of some of the ETNOs as part of a transient population. A transitional nature, perhaps similar to that of the comets with \( a < 1000 \) AU that are interacting with Jupiter, appears to be consistent with the possible existence of a correlation between nodal distance and orbital inclination in the case of both ETNOs and extreme Centaurs (\( a > 150 \) AU but \( q < 30 \) AU) as pointed out by de la Fuente Marcos and de la Fuente Marcos (2017). In sharp contrast, many of the studies aimed at explaining the orbital architecture of the ETNO realm assume that they are a long-term stable population. However, if they are a transient population, seeking dynamical mechanisms capable of making them long-term dynamically stable may not be necessary. On the other hand, it is unclear whether the orbital diffusion scenario recently proposed by Bannister et al. (2017) can produce pairs of orbitally correlated ETNOs, or not.

Our results indicate that a planet with a mass in the range 10–20 \( \text{M}_\oplus \) moving in a moderately eccentric (0.1–0.4) and inclined (20–50°) orbit with semi-major axis of 300–600 AU, may be able to trigger the dissociation of a binary ETNO following an orbit like the ones assumed here and induce a tilt similar to those observed on a time-scale of 5–10 Myr. Perturbers with \( M_{\text{TPP}} < 10 \text{M}_\oplus \) or \( a_{\text{TPP}} > 600 \) AU are unable to produce the desired effects. Such a perturber should be currently located well away from perihelion in order to have eluded detection by past surveys; this is to be expected in dynamical terms as well, due to its eccentric orbit. On the other hand, the orbital solution that is most effective in triggering binary stripping events actually reaches aphelion towards the Galactic plane, not far from the regions that surround the clouds of Sagittarius, where the stellar density is the highest and outer Solar System surveys refuse to observe, to avoid a fog of false positives. This probable coincidence reminds us that such perturber may be hidden in plain sight if it is currently moving projected towards those regions of the sky customarily avoided by surveys. Regarding its origin, planets similar to Uranus or Neptune (super-Earths) may form at 125–750 AU from the Sun (Kenyon and Bromley 2015, 2016). Within this hypothetical context, smaller bodies can also form in the same region prior to the actual planets—in perhaps wide binaries. This scenario is however inconsistent with the one proposed by Levison et al. (2008)
that argues that most TNOs may have formed in the region interior to $\sim 35 \text{ AU}$ and subsequently scattered outwards by interactions with Neptune. Alternatively, such planet may have been scattered out of the region of the Giant planets early in the history of the Solar System (Bromley and Kenyon 2016) or even captured from another planetary system (Li and Adams 2016; Mustill et al. 2016) when the Sun was still a member of the open star cluster where it was likely formed.

Although binary ETNOs have not yet been discovered, mechanisms capable of forming binaries in the outer Solar System have been discussed in the literature (see e.g. Goldreich et al. 2002; Weidenschilling 2002; Astakhov et al. 2005; Schlichting and Sari 2008; Nesvorný et al. 2010). In fact and as pointed out above, Fraser et al. (2017a, 2017b) have found that the blue-coloured (spectral slope $< 17\%$), cold TNOs are predominantly in tenuously bound binaries and proposed that they were all born as binaries at $\sim 38 \text{ AU}$. The pair of ETNOs discussed here are blue-coloured; the spectral slope of $\text{(474640) } 2004 \text{ VN}_{112}$ is $12\pm 2\%$ and that of $\text{2013 RF}_{98}$ is $15\pm 2\%$ (de León et al. 2017). However, it is certainly too early to reach a final conclusion on the actual place or places of origin of the ETNOs.

7 Conclusions

In this paper, we explore a dynamical pathway that may lead to the present-day pair of ETNOs $\text{(474640) } 2004 \text{ VN}_{112}$–$\text{2013 RF}_{98}$ and find that close encounters between extremely wide binary ETNOs and a trans-Plutonian planet can trigger binary dissociation. The relative orbital properties of the unbound pairs resulting from these interactions resemble those of some documented ETNO pairs, including the peculiar $\text{474640}$–$\text{2013 RF}_{98}$. The presence of possible former binaries among the known ETNOs has profound implications regarding the interpretation of the observed anisotropies in the distributions of the directions of the orbital poles and perihelia of the ETNOs. Summarizing:

1. We confirm that the pair of ETNOs $\text{474640}$–$\text{2013 RF}_{98}$ is an outlier in terms of relative orbital orientation within the currently known sample of ETNOs.

2. Wide binary ETNOs can dissociate during close encounters with putative trans-Plutonian planets. Most binary dissociation events are the result of close encounters at minimum approach distances inside $0.25 \text{ AU}$. For encounters below $1 \text{ AU}$ over $20\%$ of the binaries become unbound pairs; nearly $75\%$ of all the binaries reaching separations from the perturber under $0.01 \text{ AU}$ are disrupted.

3. Unbound pairs resulting from binary dissociation events may have relatively different values of the semi-major axis and eccentricity but very similar values of the orbital inclination, longitude of the ascending node, and argument of perihelion parameters. The difference in time of perihelion passage ranges from weeks to centuries, but grows rapidly over time.

4. The unbound pairs are expected to move initially along paths featuring similar directions of the perihelia, orbital poles, and perihelion/aphelion velocities.

5. The unbound pairs can experience further, longer-range interactions with the perturber that may steadily increase their relative inclination, longitude of the ascending node, and argument of perihelion. These changes will make the angular separation between their orbital poles and perihelia progressively greater.

6. The existence of former binaries among the ETNOs may signal the transient nature of many or all of them. If they are a transient population, seeking dynamical mechanisms able to make them long-term dynamically stable may not be necessary.

The research presented here must be understood as a proof-of-concept numerical exploration, not as an attempt at identifying the actual parameters of the trans-Plutonian planet that probably triggered the formation of the unbound pair of ETNOs $\text{474640}$–$\text{2013 RF}_{98}$. Multiple versions of the perturber (see Fig. 3) can lead to binary dissociation events similar to the ones described here, but the actual probability of disruption depends strongly on the geometry of the encounter. Very precise orbital solutions of the unbound pair under study are required to pursue a high-precision investigation in which the backwards integration of their orbits subjected to the action of a perturber leads to a bound couple (assuming that they were originally bound).

Although the strength of disruptive encounters and the properties of the unbound couples depend on the choice of parameters and the time interval, our full $N$-body investigation captures the essence of the binary dissociation mechanism and firmly establishes its relevance within the ETNO context. As pointed out above, binary ETNOs have not yet been discovered and the known ETNOs have not been thoroughly studied regarding binarity so they are assumed to be singles. Thus hypothetical wide, faint companions of ETNOs could be challenging targets for the future.

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