Dynamically correlated minor bodies in the outer Solar system

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ABSTRACT

The organization of the orbits of most minor bodies in the Solar system seems to follow random patterns, the result of billions of years of chaotic dynamical evolution. Much as heterogeneous orbital behaviour is ubiquitous, dynamically coherent pairs and groups of objects are also present everywhere. Although first studied among the populations of asteroids and comets that inhabit or traverse the inner Solar system, where they are very numerous, at least one asteroid family has been confirmed to exist in the outer Solar system and two other candidates have been proposed in the literature. Here, we perform a systematic search for statistically significant pairs and groups of dynamically correlated objects through those with semimajor axis greater than 25 au, applying a novel technique that uses the angular separations of orbital poles and perihelia together with the differences in time of perihelion passage to single out pairs of relevant objects. Our analysis recovers well-known, dynamically coherent pairs and groups of comets and trans-Neptunian objects and uncovers a number of new ones, prime candidates for further spectroscopic study.

Key words: methods: statistical – celestial mechanics – comets: general – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud.

1 INTRODUCTION

Collisional break-ups, rotational or thermal-stress-induced splittings, tidal disruptions and binary dissociations all lead to the formation of pairs or groups of dynamically correlated minor bodies (see e.g. Benz & Asphaug 1999; Boehnhardt 2004; Sekanina & Chodas 2005, 2007; Bottke et al. 2006; Jacobson & Scheeres 2011; Schunová et al. 2014; Jacobson 2016; Vokrouhlický et al. 2017a); mean motion and secular resonances can also induce orbital coherence (see e.g. de laFuente Marcos & de la Fuente Marcos 2016a). Groups or families were first identified in the main asteroid belt (Hirayama 1918), but they are present in other regions of the Solar system as well (Brown et al. 2007). As many as 100 000 asteroids have been found to be members of families (see e.g. Nesvorný, Brož & Carruba 2015), but dozens of comets are also organized in families (see e.g. Sekanina & Chodas 2005).

The largest asteroid families —Nysa, Vesta, Flora and Eos— may include tens of thousands of members (see e.g. Nesvorný et al. 2015), the smallest —e.g. Datura (Nesvorný, Vokrouhlický & Bottke 2006; Nesvorný & Vokrouhlický 2006; Vokrouhlický et al. 2009; Vokrouhlický et al. 2017b; Rosaev & Plávalová 2017; Henych & Holzapple 2018), Lucascavin and Emilkowalski (Nesvorný & Vokrouhlický 2006), or Haumea (Brown et al. 2007; Raguzzine & Brown 2007; Snodgrass et al. 2010; Carvy et al. 2012)— may host a few tens or less. Unbound pairs of asteroids, probably of a common origin, have also been identified (Vokrouhlický & Nesvorný 2008; Pravec et al. 2010; Jacobson 2016); one candidate pair resides in the scattered disc (Rabinowitz et al. 2011). Groups of pairs define young asteroid clusters (Pravec et al. 2018). Although there are hundreds of asteroids known to have one or more moons (see e.g. Margot et al. 2015), binary comets seem to be uncommon; there is only one confirmed example, (300163) 2006 VW139 = 288P (Agarwal et al. 2017), but comets with bimodal nuclei like 8P/Tuttle (Harmon et al. 2010) or 67P/Churyumov-Gerasimenko (Massironi et al. 2015) are known to exist. Nonetheless, several pairs of comets having nearly identical orbits have been detected (see e.g. Sekanina & Kracht 2016).

The first bona fide asteroid family identified in the outer Solar system was the one associated with dwarf planet Haumea (Brown et al. 2007). Predating this discovery by a few years, a candidate collisional family was proposed by Chiang (2002). The subject of finding collisional families of trans-Neptunian objects (TNOs) has been studied by Chiang et al. (2003) and Marcus et al. (2011). Here, we perform a systematic search for statistically significant pairs and groups of comets and trans-Neptunian objects and uncovers a number of new ones, prime candidates for further spectroscopic study.

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2 WHAT TO EXPECT AFTER DISRUPTION

The first step in searching for dynamically correlated minor bodies, particularly those resulting from break-ups, is to get a clear characterization of what the expectations may be. The outcome of cometary disruption is well documented through two well-studied examples, those of the comets 73P/Schwassmann-Wachmann 3 and 1993 F2 (Shoemaker-Levy 9). For reasons that still remain unclear, comet 73P started to break apart in 1995 and dozens of fragments were observed in 2006 and 2007 (see e.g. Crovisier et al. 1996; Weaver et al. 2006; Reach et al. 2009; Hadamcik & Levasseur-Regourd 2016). Some of these fragments have been recovered in 2010–2011 (Harker et al. 2011, 2017; Sitko et al. 2011) and 2016–2017 (e.g. Kadota et al. 2017; Williams 2017); it may consist of hundreds of pieces now (68 of them have orbit determinations). This fragmentation process can be described as gentle and progressive. In striking contrast, comet Shoemaker-Levy 9 experienced a sudden, violent fragmentation event triggered by strong tidal forces during a close encounter with Jupiter in 1992 July (see e.g. Sekanina, Chodas & Yeomans 1994, 1998; Ashbaugh & Benz 1996; Sekanina 1997). Most fragments collided with Jupiter over a period of a week (1994 July 16–22); 21 of them have orbit determinations.

Quite different may have been the collisional event that led to the formation of the Haumea family (Brown et al. 2007; Schlichting & Sari 2009; Leinhardt, Marcus & Stewart 2010; Lykawka et al. 2012; Ortiz et al. 2012) perhaps more than 1 Gyr ago (Raguzine & Brown 2007; Volk & Malhotra 2012). Fragments of recently disrupted minor bodies must have very similar values of their semimajor axis, a, eccentricity, e, inclination, i, longitude of the ascending node, Ω, argument of perihelion, ω, and time of perihelion passage, τp, but Ω, ω and τp tend to become increasingly randomized over time. In contrast, recently unbound pairs resulting from binary dissociation events might have relatively different values of a and e, but very similar values of i, Ω and ω. The difference in τp may initially range from weeks to centuries, but grows rapidly over time (see e.g. de León, de la Fuente Marcos & de la Fuente Marcos 2017; de la Fuente Marcos, de la Fuente Marcos & Aarseth 2017).

In this paper, we use the dynamical signatures left by the three fragmentation events mentioned before —in the form of distributions of possible values of certain parameters— to single out dynamically coherent pairs and groups of minor bodies. We focus on the values of the angular separations between the poles, α, and perihelia, ω, of the orbits of the members of the pair calculated as described by e.g. de la Fuente Marcos & de la Fuente Marcos (2016b), and the differences in their times of perihelion passage, Δτp. We start by computing the distributions of α, ω and Δτp for the objects associated with those three fragmentation episodes, but the procedure described here is applied in other sections as well. Our calculations use the values of i, Ω, ω, and τp for real objects, and their respective standard deviations, σi, σΩ, σω, and στp. The source of the data in our table and figures is Jet Propulsion Laboratory’s Solar System Dynamics Group Small-Body Database (JPL’s SSDG SBDB; Giorgini, Chodas & Yeomans 2001; Giorgini 2011, 2015).1 and we restrict the analysis to objects with σi/a<0.05 (data as of 2017 October 3), where σi/a is the value of the standard deviation of i/a. In order to produce the distributions of α, ω, and Δτp, we generate 107 random pairs of virtual objects and compute for each one of them the values of α, ω, and Δτp. The orbit of each random virtual object is calculated using the means and standard deviations of the orbit determinations of real objects. For example, in order to compute a new random value of Ω, the expression Ω = (Ω) + σΩr1 is used, where (Ω) is the longitude of the ascending node of the random orbit, (Ω) is the mean value of the longitude of the ascending node of one real object, σΩ is its associated standard deviation, and r1 is a (pseudo-) random number with a normal distribution in the range −1 to 1. The same procedure is utilized for the other orbital elements. Each virtual pair has been generated using the means and standard deviations of the orbit determinations of two different real objects.

Fig. 1 shows the distributions of possible angular separations, α, and of also Δτp for the outcomes of the three events mentioned before. The dynamical signature associated with comet 73P (Fig. 1, left-hand panels) has been computed using 45 fragments, those with σi/a<0.05. A disruption episode that is taking place over an extended period of time, two decades, leaves a signature with α<1° and α<0.6; the distribution in Δτp reflects the fact that different groups of fragments have been observed at different epochs and that these fragments have been released at various times. The distributions obtained for the 21 fragments of Shoemaker-Levy 9 (Fig. 1, central panels) are mostly consistent with those of comet 73P, α<0.25 and α<0.7, with ∆τp<10 d. These results show that any fragments produced by a relatively recent disruption event must have low values of α and Δτp, probably under ∼2°; on the other hand, the value of ∆τp must be significantly shorter than the average orbital period of the fragments. In striking contrast, fragments from an old disruption episode may have values of α uniformly distributed in the interval (0, 180°), values of ∆τp spanning the entire relevant orbital period of the fragments, and a wide range in the values of α as observed in the case of the Haumea family (Fig. 1, right-hand panels). The distributions for the Haumea family have been computed using the following TNOs (see e.g. Thirion et al. 2016): (136108) Haumea 2003 EL41, (24835) 1995 SM25, (19308) 1996 TO66, (86047) 1999 OY5, (55636) 2002 TX900, (120178) 2003 OP2, (2003 SQ37 (416400) 2003 UZ117, (308193) 2005 CB9, (145543) 2005 RR43 and (386723) 2009 YE7. The average values and standard deviations of a, e, i, Ω and ω for the Haumea collisional family (11 assumed members) are 43.2±0.7 au, 0.13±0.03, 27.5±1.4, 184°±105 and 197°±98°, i.e. the values of Ω and ω are consistent with those from a uniform distribution, 180°±104°. Dwarf planet Haumea also hosts two moons —Hi’iaka (Brown et al. 2005) and Namaka (Brown et al. 2006)— and one ring (Ortiz et al. 2017). Hereinafter, our approach assumes that the values of the relevant angular separations of any pair of interest will resemble those in Fig. 1, left-hand and central panels; this assumption can only lead to uncover very recent (in astronomical terms) disruption events. The pair of values α and Δτp is used as a proxy to assess the degree of dynamical coherence, i.e. the lower the values, the higher the level of coherence. The value of Δτp is utilized to estimate the dynamical age.

3 RELEVANT GLOBAL DISTRIBUTIONS

In order to single out statistically significant pairs of dynamically correlated objects, we have computed the distributions of α, ω, and Δτp at various distance ranges using the procedure described in the previous section. Fig. 2 is conceptually similar to Fig. 1, but now larger sets of mostly unrelated objects are used; minor bodies with semimajor axis in the range 25–50 au (1358 objects) are analysed in the left-hand panels, those with values in the range 50–150 au

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1 http://www.minorplanetcenter.net/mpec/X17/K17C79.html
2 https://ssd.jpl.nasa.gov/sbdb.cgi
Dynamically correlated comets and TNOs

(335) are plotted in the central panels, and those with $a>150$ au (40) appear in the right-hand panels. For the range 25–50 au, the probability of finding a pair with both $\alpha_p$ and $\alpha_q$ under $2^\circ$ is $3.8 \times 10^{-4}$, at 50–150 au is $4.5 \times 10^{-3}$, and beyond 150 au is $<10^{-7}$ (probabilities calculated in the usual way; see e.g. Wall & Jenkins 2012). These very low $p$-values mean that pairs of dynamically coherent minor bodies in the outer Solar system are rare, but also that the ones found are probably statistically significant —i.e. not due to chance—with few interlopers. The distribution of possible angular separations between poles (Fig. 2, middle panels) shows two peaks for TNOs with semimajor axis in the range 25–50 au (left-hand, middle panel). The primary maximum at about $3^\circ$ corresponds to the cold population described by e.g. Petit et al. (2011), while the secondary one at about $9^\circ$ (far less obvious than the primary one) signals the transition to the hot population (see Fig. 3). The peaks at $a \in (25, 50)$ au are well below the single peak observed for TNOs with $a \in (50, 150)$ au at nearly $21^\circ$ (Fig. 2, central, middle panel) and its relative frequency is lower; data for $a>150$ au are still very incomplete, but the peak appears to be closer to $30^\circ$ (Fig. 2, right-hand, middle panel) and its relative frequency lower than those of the inner TNOs (see Fig. 2, left-hand and central, middle panels). The three cumulative distributions are very different, with that of TNOs with $a>150$ au showing the effects of a significant fraction of retrograde orbits (17.5 per cent), which are relatively scarce for TNOs with $a<150$ au (1.7 per cent). The origin of the large difference in the fraction of retrograde orbits remains unclear, but the presence of one or more yet-to-be-discovered planetary bodies orbiting the Sun well beyond Neptune may be able to explain such dissimilarity (see e.g. de la Fuente Marcos, de la Fuente Marcos & Delporte, 128P/Shoemaker-Holt 1, 141P/Machholz 2 (Sekanina 1999), 205P/Giacobini, 213P/Van Ness, 332P/Ikeya-Murakami (Jewitt et al. 2016; Kleya et al. 2016), C/2003 S4 (LINEAR), P/2004 V5 (LINEAR-Hill), P/2013 R3 (Catalina-PANSTARRS) (Jewitt et al. 2017) and P/2016 J1 (PANSTARRS) (Hui, Jewitt & Du 2017b). In addition, we recovered the pair C/2002 A1 (LINEAR) and C/2002 A2 (LINEAR) discussed by Sekanina et al. (2003), the pair 169P/NEAT and P/2003 T12 (SOHO) found by Sosa & Fernández (2015), the pair C/1996 Q1 (Tabur) and C/2015 F3 (SWAN) identified by Sekanina & Kraetch (2016), and a number of previously unknown ones (non-exhaustive list), 10P/Tempeel 2 and P/2015 T3 (PANSTARRS), 208P/McMillan and P/2011 Q5 (McNaught), 342P/SOHO and P/2002 S7 (SOHO), 16P/Brooks 2 and 307P/LINEAR, and 285P/LINEAR and P/2013 N5 (PANSTARRS). Of particular interest could be P/2010 B2 (WISE) that appears to be related to the multiple fragments of comet 332P/Ikeya-Murakami, confirming the analysis carried out by Hui, Ye & Wiegert (2017a). All these pairs and groups of fragments have very small values of both $\alpha_p$ and $\alpha_q$ ($<2^\circ$) and in some cases very small values of $\Delta q_\tau$ (less than a few months). The probability of finding two comets with $a<1000$ au and both $\alpha_p$ and $\alpha_q$ under $2^\circ$ is about 0.0031; if we add the constraint of having $|\Delta q_\tau|<1$ yr, the probability is 0.0026 that we interpret as strong evidence that the vast majority of orbitally coherent comets must be the result of very recent splitting events. The data currently available suggest that it is easier to find dynamically correlated candidate pairs among comets than among asteroids and that comets do not tend to keep fragments gravitationally bound after disruption (i.e. binary or higher multiplicity comets are truly uncommon). On the other hand, there is at least one example of a pair of very long-period comets, C/1988 F1 (Levy) and C/1988 J1 (Shoemaker-Holt), with relative differences in $a$, $e$, $i$, $\Omega$, $\omega$ and $\tau_r$, as low as 8.7 au, 0.00006, 0.0033, 0.0015, 0.0073 and 76.33 d, respectively (Sekanina & Kraetch 2016); such comets must be genetically related and the fragmentation event that led to them must have happened at
hundreds of astronomical units from the Sun. Regarding the distribution of possible angular separations between poles, Fig. 4, middle panel, shows a not-well-defined peak at about 15°. As a closing remark for this section, our approach is confirmed to be statistically robust as multiple, well-established results are reproduced.

4 SOME STATISTICALLY SIGNIFICANT PAIRS

Here, we apply the procedure described in the previous sections to find pairs and groups of dynamically correlated objects in the outer Solar system. Table 1 only shows our most significant findings, a more exhaustive analysis will be presented in a future paper.

4.1 Semimajor axes in the range 25–50 au

Our preliminary search indicates that the pair with the highest level of orbital coherence (see Table 1) is the one composed of (134860) 2000 OJ₂₇ (Buie et al. 2000) and 2001 UP₈₆ (Wasserman et al. 2002) with \(a_p = 0.1825 \pm 0.0010\), \(a_q = 0.1586 \pm 0.04\) and \(|\Delta\tau| = 21 \pm 145\) d. The statistical significance of the pair 134860–2001 UP₈₆ has been estimated by computing the probability of finding a pair with lower values of both \(\Delta\tau\) and \(|\Delta\tau|\) among the \(10^7\) random pairs of virtual objects generated to single this one out; the value is \(1.36 \pm 2.2 \times 10^{-6}\). In order to evaluate the reliability of this result, we have generated a control sample of virtual TNOs with identical values of means and standard deviations but assigning random (i.e. uniformly distributed) values of \(\Omega\) and \(\omega\), from this control sample, the probability of finding a pair of TNOs as correlated as 134860–2001 UP₈₆ or better is \(3.4 \pm 2.8 \times 10^{-7}\) (mean values and standard deviations from 10 sets of experiments). Assuming that the input sample is reasonably unbiased, this result may be interpreted as a confirmation that this pair might be statistically significant (at the 3.7σ level). TNO 134860 is a binary itself (Stephens & Noll 2006; Grundy et al. 2009), part of the classical trans-Neptunian belt, and one cannot avoid speculating that 2001 UP₈₆ may be a former tertiary companion of 134860. The spectral slope or gradient of the primary of 134860 is \(26 \pm 3\%/100\) nm and the combined value for both primary and secondary is \(34\%/100\) nm (Hainaut, Boehnhardt & Pollack 2012); on the other hand, the spectral slope of 2001 UP₈₆ is \(16\pm 4\%/100\) nm (Sheppard 2012). We have found that several other TNOs — e.g. (45802) 2000 PV₁₉, 2000 PW₂₉, 2001 FL₁₉₅, 2001 OK₁₀₀₈, 2004 KF₁₉, 2006 HB₁₂₅ —

3 This TNO has only six observations with an arc length of 5139 d. The orbit determination provided by the Minor Planets Center is quite different from the one computed by JPL’s SSDG and used here.
2007 DS$_{101}$ or 2013 GX$_{136}$—have relevant angular separations within few degrees of 134860, so the presence of a collisional family is fairly likely. Fig. 5, left-hand panels, shows the distributions in $a_p$, $e$ and $\Delta \tau$ for the 10 candidates to constitute a collisional family; the distributions of possible angular separations between perihelion and poles for possible members of this dynamically coherent group certainly resemble what is seen in Fig. 1, left-hand and central panels. The average values and standard deviations of $a$, $e$, $\Omega$ and for the 10 candidate members are $45 \pm 2$ au, $0.08 \pm 0.07$, $133 \pm 0.5$, $124^\circ \pm 83^\circ$ and $146^\circ \pm 63^\circ$. On the other hand, the values of $J - H$ of 45802, and 2001 OK$_{198}$ are $0.43 \pm 0.29$ and $0.43 \pm 0.28$, respectively, which compare well with that of 134860, 0.31 $\pm$ 0.16 (Hainaut et al. 2012). If this group of objects forms a collisional family, the event that might have triggered its formation should have occurred less than a few Myr ago (compare Fig. 1 and Fig. 5, left-hand panels). Given the fact that the values of $a$ span the range 42.7–48.5 au, the proposed TNO family includes objects from both the kernel and the stirred components of the trans-Neptunian belt as characterized by Petit et al. (2011).

A similar case is found for the pair 2003 UT$_{301}$–2004 VB$_{311}$ (see Table 1) which has $a_p = 0.1394 \pm 0.0002$, $e_p = 0.9 \pm 0.6$ and $|\Delta \tau| = 1726 \pm 184$ d. Following the approach discussed above, the probability of finding a pair with lower values of both $a_p$ and $e_p$ is $4.6 \pm 1.4 \times 10^{-7}$, while the value from an equivalent sample with random $\Omega$ and $\omega$ is $9.5 \pm 5.9 \times 10^{-7}$. In this case, it is not possible to argue that the pair is statistically significant. TNOs 2003 UT$_{301}$ (Wasserman et al. 2004) and 2004 VB$_{311}$ (Petit et al. 2011) may also be dynamically coherent with (33001) 1997 CU$_{29}$, 1999 OC$_{4}$, 2000 PA$_{30}$ and 2003 HG$_{57}$. TNO 33001 shows a very red spectrum with absorption due to water ice probably in amorphous state (Barucci et al. 2000); 2003 HG$_{57}$ is a known binary with a somewhat neutral spectrum (Fraser, Brown & Glass 2015).

Fig. 5, central panels, shows the relevant distributions. The average values and standard deviations of $a$, $e$, $i$, $\Omega$ and $\omega$ for the six objects are $44 \pm 2$ au, $0.09 \pm 0.05$, $1:4:0.6$, $25^\circ \pm 38^\circ$, and $231^\circ \pm 37^\circ$. This group, if real, is clearly much younger than the one linked to the pair 134860–2001 UP$_{15}$; the spreads in $a_p$ and $e_p$ are narrower (compare left-hand and central panels in Fig. 5), as are those in $\Omega$ and $\omega$. Again, the set of objects includes members of both the kernel and the stirred components.

Another interesting pair is the one made of 2002 CU$_{154}$ (Millis et al. 2002) and 2005 CE$_{191}$ (Petit et al. 2011) which has $a_p = 0.3903 \pm 0.0007$, $e_p = 1.1 \pm 0.4$ and $|\Delta \tau| = 1451 \pm 95$ d (see Table 1). The probability of finding a pair with lower values of both $a_p$ and $e_p$ is $6.2 \pm 0.5 \times 10^{-6}$, while the value from an equivalent sample with random $\Omega$ and $\omega$ is $8.6 \pm 1.4 \times 10^{-6}$. Again, it is not possible to argue that the pair is statistically significant. Other TNOs that may be dynamically correlated with this pair are 2001 FK$_{191}$, 2003 QY$_{99}$, 2011 BV$_{163}$ and 2015 FS$_{153}$. TNO 2003 QY$_{99}$ is a known binary (Grundy et al. 2011). Fig. 5, right-hand panels, shows the relevant distributions that resemble those of 134860–2001 UP$_{15}$. The average values and standard deviations of $a$, $e$, $i$, $\Omega$ and $\omega$ for the six objects are $44 \pm 2$ au, $0.08 \pm 0.03$, $3:6:0.5$, $102^\circ \pm 7^\circ$, and $53^\circ \pm 17^\circ$. This family, if real, may be as young or even younger than the one linked to the pair 2003 UT$_{301}$–2004 VB$_{311}$. As in the previous two candidate families, the presumed members belong to the kernel and the stirred components of the dynamically cold trans-Neptunian belt.

We also recover the pair 2000 FC$_{5}$–2000 GX$_{146}$ which has $a_p = 0.1536 \pm 0.0005$, $e_p = 2.3 \pm 1.6$ and $|\Delta \tau| = 513 \pm 390$ d (see Table 1). These two TNOs are part of the candidate collisional family originally proposed by Chiang (2002), but apparently later retracted by Chiang et al. (2003), although the original result has been somewhat vindicated by Petit et al. (2011) and Marcus et al. (2011). The probability of finding a pair with lower values of both $a_p$ and $e_p$ is $3.1 \pm 0.4 \times 10^{-6}$, while the value from an equivalent sample with random $\Omega$ and $\omega$ is $1.8 \pm 0.7 \times 10^{-6}$. Therefore, this pair might be statistically significant (at the 1.9 $\sigma$ level). Other TNOs that belong to the kernel or the stirred components and that may be dynamically related to this pair are (15760) 1992 QB$_{8}$, (2000 QN$_{521}$, 2002 CY$_{158}$, 2002 PV$_{170}$, 2005 VA$_{125}$, 2010 TG$_{192}$ and 2015 GS$_{60}$. Using these TNOs we obtain the distributions in Fig. 6, left-hand panels, that clearly resemble what is expected of an event of progressive fragmentation like that of 73P (see Fig. 1, left-hand panels). The average values and standard deviations of $a$, $e$, $i$, $\Omega$ and $\omega$ for the nine objects are $44 \pm 2$ au, $0.10 \pm 0.09$, $1:2:0.6$, $221^\circ \pm 143^\circ$, and $139^\circ \pm 141^\circ$. Not counting Charon, 15760 was the second TNO to be discovered after the dwarf planet Pluto (Jewitt & Luu 1993; Luu, Jewitt & Marsden 1993). This candidate family is certainly older than those associated with the pairs 2003 UT$_{301}$–2004 VB$_{311}$ or 2002 CU$_{154}$–2005 CE$_{191}$ and the presence of secondary maxima may be attributed to create this group.

Yet another pair of interest that seems to be signalling the presence of an additional collisional family is composed of 2003 HF$_{57}$ (Kavelaars et al. 2009) and 2013 GG$_{117}$ (Bannister et al. 2016) — see Table 1 — with $a_p = 1.7844 \pm 0.0012$, $e_p = 1.8 \pm 0.6$ and $|\Delta \tau| = 160 \pm 124$ d. The probability of finding a pair with lower values of both $a_p$ and $e_p$ is $2.76 \pm 0.02 \times 10^{-4}$, while the value from an equivalent sample with random $\Omega$ and $\omega$ is $2.19 \pm 0.10 \times 10^{-4}$.
Therefore, this pair might be statistically significant (at the 5.6σ level). Other TNOs that could be dynamically related to this pair are 1998 WY₃₁, 2000 ON₇₆, 2001 FL₁₉₁, 2003 QX₉₀₁, 2005 JP₇₉ and 2006 HW₁₂₂. The presence of one object, 2001 FL₁₉₁, in common with the group associated with the pair 134860–2001 UP₁₈ may hint at a possible relationship between the two groups of TNOs or, more likely, that this object is an interloper—or even that its orbit determination cannot be trusted, see footnote (3). This set of TNOs defines the distributions in Fig. 6, right-hand panels, and again the presence of secondary maxima (top panel) hints at multiple disruption events as in the case of the group linked to 2000 FC₅₋2000 GX₁₄₆. The average values and standard deviations of $\alpha$, $e$, $i$, $\Omega$ and $\omega$ for the eight objects are $43 \pm 2$ au, $0.09 \pm 0.06$, $2.1 \pm 0.8$, $73.3 \pm 31.1^\circ$, and $100^\circ \pm 31^\circ$. These values suggest that this group could be as young as those associated with the pairs 2003 UT₉₀₋2004 VB₁₁₁ or 2002 CU₁₅₄₋2005 CE₁₁₁, but the distributions in Fig. 6, right-hand panels, indicate that it could be older than the collisional family linked to the pair 2000 FC₅₋2000 GX₁₄₆.

Several other relevant pairs are slightly less significant and may be linked to additional families, but they will not be discussed here. The statistical significance of individual pairs is expected to be strongly contingent on the quality and completeness of the input data; if there is a finite number of collisional families, the probabilities may depend on the degree of completeness in which each family is represented within the available data. Petit et al. (2011) pointed out that the presence of collisional families like the one probably linked to the pair 2000 FC₅₋2000 GX₁₄₆ and previously discussed by Chiang (2002) is supported by the observational data, and that grazing impacts like those discussed by Leinhardt et al. (2010) can produce low-speed families. If the dynamically coherent groups discussed here are confirmed to be genetic families, then it may be possible that such grazing collisions could be actively grinding relatively large TNOs (of hundreds of km) up. An alternative scenario would place the source of the observed dynamical coherence in mean motion and secular resonances, but it is unclear how this might work. However, the data suggest that the stirred cold population might just be a splattered counterpart of the kernel component as objects in the 2:1, 3:2 mean motion resonances with 4.2 Semimajor axes in the range 50–150 au appear to be correlated to cold disc kernel objects.

### 4.2 Semimajor axes in the range 50–150 au

In general, the quality of the orbits of TNOs with $a \in (50, 150)$ au is lower than that of the objects analysed in the previous section and the available samples are more likely to be affected by observational biases and incompleteness issues. Most of the TNOs in this region have dynamically hot orbits, with a very small fraction of dynamically cold objects. Volk & Malhotra (2017) have presented robust statistical evidence that the mean plane of the trans-Neptunian

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**Table 1.** Orbital elements with 1σ uncertainties of statistically significant pairs of TNOs. For each pair, the values of $\alpha_p$, $\sigma_\alpha$, $\sigma_\epsilon$, $\sigma_i$, $\sigma_\Omega$, $\sigma_\omega$, $\sigma_\tau_\rho$, $\sigma_\tau_q$, $\sigma_\Delta_\tau_\rho$, $\sigma_\Delta_\tau_q$, $\Delta_{\tau_\rho}$, and $\Delta_{\tau_q}$ are listed. The orbital solutions have been computed at epoch JD 2458000.5 that corresponds to 00:00:00.000 TDB on 2017 September 4, J2000.0 ecliptic and equinox. Source: JPL’s SSDG SBDB.

| Object          | $a$ (au) | $\sigma_\alpha$ (au) | $\epsilon$ | $\sigma_\epsilon$ | $i$ (°) | $\sigma_i$ | $\Omega$ (°) | $\sigma_\Omega$ | $\omega$ (°) | $\sigma_\omega$ | $\tau_\rho$ (JD) | $\sigma_\tau_\rho$ (d) | $\tau_q$ (JD) | $\sigma_\tau_q$ (d) | $\Delta_{\tau_\rho}$ (d) | $\Delta_{\tau_q}$ (d) |
|-----------------|---------|----------------------|------------|-------------------|--------|-----------|-------------|----------------|-------------|----------------|---------------|----------------------|---------------|----------------------|--------------------------|----------------------|
| (134860) 2000 OJ₆₇ | 42.762  | 0.011                | 0.02304    | 0.0012           | 1.1147 | 0.0002    | 96.795      | 0.014          | 145.4       | 0.5           | 2430267       | 124                   |               |                      |                          |                     |
| (135571) 2002 GG₁₂ | 55.88   | 0.04                  | 0.3583     | 0.0005           | 14.6596 | 0.0013    | 35.6950     | 0.0012         | 230.73      | 0.12          | 2460137       | 21                    |               |                      |                          |                     |
| (135571) 2002 GG₁₂ | 55.88   | 0.04                  | 0.3583     | 0.0005           | 14.6596 | 0.0013    | 35.6950     | 0.0012         | 230.73      | 0.12          | 2460137       | 21                    |               |                      |                          |                     |
Dynamically correlated comets and TNOs

Figure 5. Distributions of possible angular separations between perihelia (top panels) and poles (middle panels), and differences in time of perihelion passage (bottom panels) of the orbits of pairs of TNOs associated with (134860) 2000 OJ$_{67}$–2001 UP$_{18}$ (left-hand panels), 2003 UT$_{291}$–2004 VB$_{131}$ (central panels), and 2002 CU$_{152}$–2005 CE$_{81}$ (right-hand panels).

Figure 6. Distributions of possible angular separations between perihelia (top panels) and poles (middle panels), and differences in time of perihelion passage (bottom panels) of the orbits of pairs of TNOs associated with 2000 FC$_{3}$–2000 GJ$_{46}$ (left-hand panels) and 2003 HY$_{27}$–2013 GJ$_{137}$ (right-hand panels).

belt is warped in a manner that an inclined, low-mass (probably Mars-sized), unseen planet at an average distance from the Sun of around 60 au could be responsible for the warping. Such a perturber may also induce (or help wipe out) orbital coherence.

One pair of correlated objects is (135571) 2002 GG$_{1}$, a red object with a spectral slope of 34±3%/100 nm (Sheppard 2012), and (160148) 2001 KV$_{56}$ (Elliot et al. 2005) which has $\alpha_p = 1^\circ 1840\pm0:0009$, $\alpha_q = 1^\circ 75\pm0:14$ and $|\Delta\alpha_p| = 1081\pm23$ d. Using the approach discussed in the previous section, the probability of finding a pair with lower values of both $\alpha_p$ and $\alpha_q$ is $7.4 \pm 1.1 \times 10^{-6}$. 
while the value from an equivalent sample with random $\Omega$ and $\omega$ is $2.1\pm1.5\times10^{-5}$. Such a large difference in the values of the probabilities must be the result of strong non-uniformity in the distributions of the observed values of $\Omega$ and $\omega$ that could be due to observational bias or selection effects, or (perhaps more likely) induced by an unseen perturber. The two orbits exhibit a high degree of coherence in terms of the angular elements and $\tau$, but their values of $a$ and $e$ are very different (see Table 1). This is consistent with binary dissociation induced by a close encounter with a massive body, not fragmentation (see e.g. de la Fuente Marcos et al. 2017). A similar case is found for the pair 2005 GX201 (Gibson et al. 2016a) and 2015 BD19 (Gibson et al. 2016c) with $a_p = 1.4021 \pm 0.0003$, $a_e = 1.434 \pm 0.010$ and $|\Delta \tau| = 16.490 \pm 12$ d. The probability of finding a pair with lower values of both $a_p$ and $a_e$ is $7.6\pm0.9\times10^{-6}$, while the value from an equivalent sample with random $\Omega$ and $\omega$ is $1.8\pm1.4\times10^{-5}$. As in the previous case, the very different values of the probabilities might signal the presence of a present-day, relatively massive perturber. There are other pairs with similar statistical significance.

Another pair of potentially interesting objects (not shown in Table 1) is the one composed of 2012 OL$_4$ (Sheppard & Trujillo 2016) and 2014 WS$_{160}$ (Gibson et al. 2016b) which has $a_p = 0.185 \pm 0.008$, $a_e = 8' \pm 6'$ and $|\Delta \tau| = 49.002 \pm 3.884$ d. Other TNOs that might be dynamically related to this pair are 2002 CZ$_{248}$ and 2013 AR$_{185}$. TNOs 2012 OL$_4$, 2014 WS$_{160}$ and 2002 CZ$_{248}$ have average values and standard deviations of $a$, $e$, $i$, $\Omega$ and $\omega$ of $54.1\pm1.1$ au, $0.35\pm0.05$, $8'\pm2'$, $153'\pm15'$, and $286'\pm22'$; in contrast, 2013 AR$_{185}$ has $a=71.7$ au. As a reference, the candidate pair in Rabinowitz et al. (2011), (471151) 2010 FD$_{90}$–(471152) 2010 FE$_{90}$, has $a_p = 1.89243 \pm 0.00013$, $a_e = 18.735 \pm 0.009$ and $|\Delta \tau| = 4019.8 \pm 1.4$ d.

4.3 Beyond 150 au

If we focus on extreme Centaurs and trans-Neptunian objects ($a>150$ au), the pair with the smallest angular separations is composed of 2013 FT$_{38}$ (Sheppard & Trujillo 2016) and 2015 KG$_{66}$ (Shankman et al. 2017) with $a_p = 3.379 \pm 0.004$, $a_e = 7.4 \pm 0.2$ and $|\Delta \tau| = 13.640 \pm 22$ d, although their $a$ and $e$ are quite different. Its probability from Fig. 2, right-hand panel, is $<0.0003$ —that of having smaller values of $a_p$ and $a_e$. This pair could be similar to (474640) 2004 VN$_{112}$–2013 RS$_{99}$ studied by de León et al. (2017) although in this case the values of $a$ and $e$ are similar. The TNO pair 474640–2013 RS$_{99}$ has $a_p = 4.055 \pm 0.003$, $a_e = 14.72 \pm 0.6$ and $|\Delta \tau| = 101 \pm 74$ d. Another pair of extreme TNOs with similar orbital elements is the one composed of 2002 GB$_{92}$ (Meech et al. 2004) and 2003 HB$_{57}$ (Kavelaars et al. 2009) which has $a_p = 5.4543 \pm 0.0006$, $a_e = 7.39 \pm 0.05$ and $|\Delta \tau| = 1856 \pm 11$ d.

5 CONCLUSIONS

In this paper, we have searched for dynamically correlated minor bodies in the outer Solar system. A novel technique that uses the angular separations of orbital poles and perihelia, together with the differences in time of perihelion passage has been described and applied to find statistically significant pairs and groups. In summary:

(i) We provide further evidence that confirms the reality of the candidate collisional family of TNOs associated with the pair 2000 FC$_{4}$–2000 GX$_{146}$ and originally proposed by Chiang (2002).

(ii) We find four new possible collisional families of TNOs associated with the pairs (134860) 2000 OJ$_{67}$–2001 UP$_{18}$, 2003 UT$_{201}$–2004 VB$_{131}$, 2002 CU$_{154}$–2005 CE$_{41}$ and 2003 HF$_{37}$–2013 GG$_{137}$.

(iii) We find a number of unbound TNOs that may have a common origin, the most significant ones are: (135571) 2002 GG$_{12}$–(160148) 2001 KF$_{76}$ and 2005 GX$_{206}$–2015 BD$_{19}$.

Our results suggest that disruptions and dissipations of minor bodies at tens or even hundreds of astronomical units from the Sun could be as common as those taking place much closer to us. Future spectroscopic observations may help in confirming the dynamical correlations found here.

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