Flipping minor bodies: what comet 96P/Machholz 1 can tell us about the orbital evolution of extreme trans-Neptunian objects and the production of near-Earth objects on retrograde orbits

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ABSTRACT

Nearly all known extreme trans-Neptunian objects (ETNOs) have argument of perihelion close to 0°. An existing observational bias strongly favours the detection of ETNOs with arguments of perihelion close to 0° and 180° yet no objects have been found at 180°. No plausible explanation has been offered so far to account for this unusual pattern. Here, we study the dynamical evolution of comet 96P/Machholz 1, a bizarre near-Earth object (NEO) that may provide the key to explain the puzzling clustering of orbits around argument of perihelion close to 0°. Recently found for the population of ETNOs, Comet 96P/Machholz 1 is currently locked in a Kozai resonance with Jupiter such that the value of its argument of perihelion is always close to 0° at its shortest possible perihelion (highest eccentricity and lowest inclination) and about 180° near its shortest aphelion (longest perihelion distance, lowest eccentricity and highest inclination). If this object is a dynamical analogue (albeit limited) of the known ETNOs, this implies that massive perturbers must keep them confined in orbital parameter space. Besides, its future dynamical evolution displays orbital flips when its eccentricity is excited to a high value and its orbit turns over by nearly 180°, rolling over its major axis. This unusual behaviour, that is preserved when post-Newtonian terms are included in the numerical integrations, may also help understand the production of NEOs on retrograde orbits.

Key words: relativistic processes – celestial mechanics – comets: individual: 96P/Machholz 1 – minor planets, asteroids: individual; 2012 VP113 – planets and satellites: individual: Earth – planets and satellites: individual: Jupiter.

1 INTRODUCTION

Two Solar system discoveries have recently puzzled the astronomical community: the existence of near-Earth objects (NEOs, perihelion distance less than 1.3 au and, if a comet, orbital period less than 200 yr) moving on retrograde orbits and the clustering of orbits around argument of perihelion, ω, close to 0° for extreme trans-Neptunian objects (ETNOs, semimajor axis greater than 150 au and perihelion distance greater than 30 au).

There are only 11 known retrograde NEOs: three asteroids – (343158) 2009 HC82, 2007 VA45, and 2014 PP49 – and eight comets (55P/Temple-Tuttle, 1P/Halley, P/2005 T4 (SWAN), C/2010 L5 (WISE), 273P/Pons-Gambart, C/2001 W2 (BATTERS), 109P/Swift-Tuttle and 161P/Hartley-IRAS). The number of known near-Earth asteroids (NEAs) is 11,490 and the number of near-Earth comets (NECs) is 165. Retrograde objects represent a tiny fraction, 0.094 per cent, of the NEO population. Numerical integrations carried out by Greenstreet et al. (2012) unveiled a dynamical mechanism capable of inducing ordinary asteroid orbits to flip to a retrograde configuration while trapped in the 3:1 mean motion resonance with Jupiter near 2.5 au. These authors predict that nearly 0.1 per cent of the NEO population could follow retrograde orbits.

Nearly all known ETNOs have ω close to 0° (the average value is 31° ± 50°, see a discussion in Trujillo & Sheppard 2014; de la Fuente Marcos & de la Fuente Marcos 2014b). An existing observational bias strongly favours the detection of ETNOs at ω close to 0° and 180° yet no objects have been found at 180° (Trujillo & Sheppard 2014; de la Fuente Marcos & de la Fuente Marcos 2014b). No plausible explanation has been offered so far to account for the apparent lack of objects with ω around 180°. The perplexing puzzle posed by the apparent lack of such objects among known members of the ETNO population is not the only unusual pattern displayed by the orbital parameters of this interesting group of trans-Plutonian objects (see fig. 3 in de la Fuente Marcos & de la Fuente Marcos 2014b). The orbital elements of these objects (see Table 1) exhibit conspicuous clustering around $e \sim 0.80$ (0.82 ± 0.06) and $i \sim 20°$ (18° ± 7°). The very high mean value of the eccentricity could be attributed, in principle, to an observational bias: for this...
Table 1. Various orbital parameters ($\varpi = \Omega + \omega, \lambda = \varpi + M$) for the 13 known ETNOs (Epoch: JD 245 7000.5 that corresponds to 0:00 UT on 2014 December 9. J2000.0 ecliptic and equinox. Source: JPL Small-Body Database.)

| Object       | $a$ (au) | $e$   | $i$ (°) | $\Omega$ (°) | $\omega$ (°) | $\varpi$ (°) | $\lambda$ (°) | $Q$ (au) |
|--------------|---------|-------|--------|---------------|--------------|--------------|--------------|--------|
| (82158) 2001 FP$_{185}$ | 222.889152 | 0.84638769 | 30.76961 | 179.31663 | 6.83700 | 186.15400 | 187.34300 | 411.5400 |
| (90377) Sedna  | 524.3945961 | 0.8549532 | 11.92862 | 144.54542 | -48.71210 | 95.83240 | 93.99530 | 792.6970 |
| (148209) 2000 CR$_{105}$ | 230.1151596 | 0.80777192 | 22.70702 | 128.23435 | -42.84210 | 90.48600 | 90.48600 | 415.9960 |
| 2002 GB$_{32}$ | 211.8626339 | 0.83318098 | 14.17959 | 176.99786 | 36.89740 | 213.98600 | 213.98600 | 388.3840 |
| 2003 HB$_{57}$ | 162.3925720 | 0.76545417 | 15.48811 | 197.84847 | 10.66603 | 209.54300 | 209.54300 | 286.6970 |
| 2003 SS$_{422}$ | 195.9581432 | 0.79878068 | 16.80711 | 151.10976 | -149.98800 | 1.84113 | 411.3400 | 352.4860 |
| 2004 VN$_{112}$ | 328.8226182 | 0.85605608 | 25.53759 | 66.03781 | -32.77670 | 411.3400 | 411.3400 | 352.4860 |
| 2005 RH$_{12}$ | 151.9398031 | 0.74329346 | 20.46837 | 306.19632 | 32.51841 | 276.19900 | 276.19900 | 286.6970 |
| 2007 TG$_{422}$ | 518.1738582 | 0.93132860 | 18.58061 | 112.97697 | -74.16600 | 39.08750 | 39.08750 | 1000.7600 |
| 2007 VJ$_{305}$ | 190.7687814 | 0.81549271 | 11.99449 | 24.38349 | -21.51450 | 40.86050 | 40.86050 | 346.3390 |
| 2010 GB$_{174}$ | 370.1872857 | 0.86864073 | 21.53245 | 130.58694 | -12.34630 | 121.14800 | 121.14800 | 691.7470 |
| 2010 VZ$_{98}$ | 155.2822279 | 0.77960350 | 4.50914 | 117.46709 | -46.15010 | 71.37180 | 68.90210 | 276.1990 |
| 2012 VF$_{113}$ | 263.1193815 | 0.6900129 | 14.17959 | 197.84847 | 10.66603 | 209.54300 | 209.54300 | 286.6970 |

2  NUMERICAL MODEL

The numerical integrations of the orbits of comet 96P/Machholz 1 studied here were performed with the Hermite integrator (Makino 1991; Aarseth 2003), in a model solar system which takes into account the perturbations by eight major planets and treats the Earth–Moon system as two separate objects; it also includes the barycentre of the dwarf planet Pluto–Charon system and the 10 most massive asteroids of the main belt, namely (1) Ceres, (2) Pallas, (4) Vesta, (10) Hygiea, (31) Euphrosyne, 704 Interamnia (1910 KU), 511 Davida (1903 L2), 532 Herculis (1904 NY), (15) Eunomia and (3) Juno (for further details, see de la Fuente Marcos & de la Fuente Marcos 2012). Results in the figures have been obtained using initial conditions (positions and velocities in the barycentre of the solar system) provided by the Jet Propulsion Laboratory (JPL) HORIZONS system (Giorgini et al. 1996; Standish 1998) and referred to the JD 245 7000.5 epoch which is the $t = 0$ instant. In addition to the calculations completed using the nominal orbital elements in Table 2 we have performed 50 control simulations with sets of orbital elements obtained from the nominal ones within the accepted uncertainties ($3\sigma$).

3  COMET 96P/MACHHOLZ 1, BIZARRE FROM EVERY ANGLE

Comet 96P/Machholz 1 was discovered on 1986 May 12 by D. E. Machholz observing with 29×130 binoculars from Loma Prieta, California (Machholz, Morris & Hale 1986) and confirmed the following days by S. Morris and A. Hale observing from near Mt. Wilson, California. It was soon clear that its orbit was very unusual, travelling closer to the Sun than any known planet, (at that time) asteroid or comet (Green et al. 1990), and displaying higher than expected activity at aphelion (Sekanina 1990). With an orbital period of 5.28 yr and a perihelion, $q$ of just 0.12 au, its eccentricity, $e$, is 0.96, and its inclination, $i$, is significant at 58.31°. Its aphelion, $Q$, is beyond Jupiter at 5.94 au. Its current orbit is based on 1090 observations with a data-arc span of 9642 days, with perturbations by eight major planets and treating the Earth–Moon system as two separate objects; it also includes the barycentre of the dwarf planet Pluto–Charon system and the 10 most massive asteroids of the main belt, namely (1) Ceres, (2) Pallas, (4) Vesta, (10) Hygiea, (31) Euphrosyne, 704 Interamnia (1910 KU), 511 Davida (1903 L2), 532 Herculis (1904 NY), (15) Eunomia and (3) Juno (for further details, see de la Fuente Marcos & de la Fuente Marcos 2012). Results in the figures have been obtained using initial conditions (positions and velocities in the barycentre of the solar system) provided by the Jet Propulsion Laboratory (JPL) HORIZONS system (Giorgini et al. 1996; Standish 1998) and referred to the JD 245 7000.5 epoch which is the $t = 0$ instant. In addition to the calculations completed using the nominal orbital elements in Table 2 we have performed 50 control simulations with sets of orbital elements obtained from the nominal ones within the accepted uncertainties ($3\sigma$).
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4 COMET 96P/MACHHOLZ 1: ORBITAL EVOLUTION

Comet 96P/Machholz 1 is a well studied Jupiter-family comet. With a semimajor axis of 3.03 au it is submitted to the 9:4 mean motion resonance with Jupiter (see i.e. Ohtsuka et al. 2003). The time evolution of the osculating orbital elements of its nominal orbit is displayed in Fig. 1. We confirm that the object is currently trapped in a Kozai resonance with Jupiter. Because of this, the eccentricity and inclination oscillate with the same frequency but out of phase (see panels D and E), when the value of the eccentricity reaches its maximum the value of the inclination is the lowest and vice versa ($\sqrt{1-e^2}\cos i = \text{constant}$). In a Kozai resonance, the apse and the node are in resonance with one another (Kozai 1962). The values of eccentricity and inclination are coupled, and the value of the semimajor axis remains nearly constant (see panels C, D and E in Fig. 1). The orbit of this object is particularly chaotic and it is difficult to make reliable predictions beyond a few thousand years. All the integrated orbits give consistent results within the time interval (-2, 6.5) kyr. Its current Kozai resonant dynamical status is firmly established. As an example, Fig. 2 displays the short-term dynamical evolution of an orbit arbitrarily close to the nominal one (central panels) and those of two illustrative worst orbits which are most different from the nominal one. The orbit labelled as '-3\sigma' (left-hand panels) has been obtained by subtracting thrice the uncertainty from the orbital parameters (the six elements) in Table 2. It has the lowest values of $a$, $e$ and $i$ at the 3\sigma level. In contrast, the orbit labelled as '+3\sigma' (right-hand panels) was computed by adding three times the value of the uncertainty to the orbital elements in Table 2. This trajectory has the largest values of $a$, $e$ and $i$ (within 3\sigma). Close encounters with Jupiter within the Hill radius (see panel A) are very frequent with one of the nodes usually close to Jupiter (see panel G). With this orbital layout, the object is necessarily transient. We have neglected the role of non-gravitational forces in our simulations because the objective of this research is not the dynamics of the comet itself but its implications for the orbital evolution of other asteroidal bodies, NEOs and ETNOs. None of the control orbits computed here will drive the comet into the Sun as predicted by Levison & Dones (2014) and others. The inclusion in the calculations of (10) Hygiea, (31) Euphrosyne, 704 Interamnia (1910 KU) and 511 Davida (1903 LU) has a major impact on the simulated evolution as the object becomes a transient, for about 1 kyr, co-orbital to some of them. Relatively close encounters with all the previously mentioned asteroids are possible.

5 FLIPPING THE ORBIT

Perhaps, the most striking feature in Figs. 1 and 2 (E-panels) is the dramatic flip from prograde to retrograde and back again observed after integrating the orbit at least 12 kyr into the future. The actual instant of the first orbital flip depends on the initial conditions but it is found in all the integrations. Some retrograde episodes are short (see Fig. 1) but longer events are possible (see Fig. 2). These
The sudden orbit flip is the result of the comet continuously losing angular momentum that is in return gained by the outer perturber, Jupiter in this case. When the comet's angular momentum is very small, a slight gravitational kick during a close encounter is enough to switch the direction of its orbit.

The mechanism proposed by Greenstreet et al. (2012) to produce retrograde NEOs is different from the one presented here. In their simulations, the role of the 3:1 mean motion resonance (near $a = 2.5$ au) is central to make the orbits retrograde. In our case, the 9:4 mean motion resonance with Jupiter is the one at work when the flip takes place at aphelion (see Figs 3 and 4). Crossing the resonance triggers the orbital flip, see Fig. 4. It is, therefore, another evolutionary pathway to produce retrograde NEOs. The existence of multiple dynamical tracks running into the retrograde orbital domain can help to explain the detection of high-velocity, rocky meteoroids on retrograde orbits (Borovička et al. 2005).

Relativistic effects, resulting from the theory of general relativity are not negligible when studying the long-term dynamical evolution of minor bodies in the innermost part of the Solar system. Comet 96P/Machholz 1 has a low perihelion distance ($q = 0.12$ au), comparable to those of the so-called relativistic asteroids (see table 2 in Benítez & Gallardo 2008). For these objects, the main effect is in the evolution of the argument of perihelion which has a direct impact on the Kozai mechanism. The inclusion of these relativistic effects in $N$-body simulations is customarily approached within the framework of the post-Newtonian approximation (see e.g. Aarseth 2007 and references therein) based on
first-order expansion. Naoz et al. (2013) have found that the inclusion of post-Newtonian contributions in the study of the Kozai mechanism in hierarchical three-body systems can, in some cases, suppress eccentricity-inclination oscillations as the ones observed above when only Newtonian terms are considered in the integrations. Figure 5 shows that this is not the case here, the unusual behaviour found in the Newtonian case is preserved under the post-Newtonian approximation. Further modifying the orbit as described in the previous section does not affect the overall results, see Fig. 6. The duration of the retrograde episodes is, in fact, longer in the post-Newtonian case.

6 COMET 96P/MACHHOLZ 1 AND THE ETNOS

The orbital evolution of comet 96P/Machholz 1 exhibits another unusual feature, when the eccentricity is at its highest, the inclination is at its lowest, and the argument of perihelion is close to 0° (see Fig. 7). This interesting property may be the key to explain the apparent lack of objects with ω around 180° found among known members of the ETNO population (see above). ETNOS can only be discovered at perihelion and if they follow an orbital evolution similar to that of comet 96P/Machholz 1, they will be preferentially found when their perihelion distance is the shortest; therefore, their eccentricity is the highest possible which in turn implies that their ω must be close to 0° at the time of discovery. Perhaps, the secular evolution of these objects is better viewed in the e-ω plane, where

\[e_r = e - e_p\] and \[\omega_r = \omega - \omega_p\]. e_p and ω_p are, respectively, the eccentricity and argument of perihelion of a given planet (Namouni 1999). In Fig. 8 we plot the \(i/e, \omega_r\)-map for comet 96P/Machholz 1 relative to Jupiter when its dynamical state is the one of interest here. The \(\omega, i/e\)-values for the ETNO population (see Table 1) are also plotted. The distribution of the orbital parameters (\(\omega, i/e\)) of most, if not all, ETNOS matches well what is expected of a Kozai librator like comet 96P/Machholz 1.

The Kozai scenario described for comet 96P/Machholz 1 is driven by the fact that the value of the aphelion distance of this comet oscillates around that of Jupiter (see Fig. 7 top panel), the perturber that controls its dynamical state. In other words, for this mechanism to work, the aphelion of a massive perturber must be located relatively close to the aphelion distance of the affected object and this putative perturber should probably move in a low-eccentricity, low-inclination orbit (see Fig. 8). If we admit that comet 96P/Machholz 1 is a good dynamical analogue for all (or part) of the ETNO population, the implications for the actual architecture of the trans-Plutonian region are multiple. First of all, massive perturbers must be orbiting near the aphelion distances of the ETNOs in order to keep them locked in their current state. In addition, some (if not all) of these objects could be transient. In Table 1 we observe four groups of aphelia. Asteroids 2003 HB57, 2005 RH52 and 2010 VZ98 have aphelia in the range 264–287 au. Asteroids (82158) 2001 FP185, (148209) 2000 CR105, 2002 GB32, 2003 SS422, 2007 VJ305 and 2012 VP113 have aphelia in the range 346–416 au. Asteroids 2004 VN112 and 2010 GB174 have aphelia...
Resonant argument, $\sigma_{9:4}$, panels D, E and C (of Fig. 1) restricted to the time interval (10, 15) kyr. The resonant argument associated to the 9:4 mean motion resonance with Jupiter becomes constant prior to the orbital flip from prograde to retrograde. The resonant argument is $\sigma_{9:4} = 9\lambda_J - 4\lambda - 5\varpi$, where $\lambda_J$ is the mean longitude of Jupiter, $\lambda$ is the mean longitude of comet 96P/Machholz 1, and $\varpi = \Omega + \omega$ is its longitude of perihelion.

Figure 4. Same as Fig. 3 but for the time interval (11.4, 12.0) kyr.

Figure 5. Same as Fig. 1 but for relativistic calculations.

This comet may be just a limited dynamical analogue to 2012 VP$_{113}$ and similar objects because it mostly moves within the inner Solar system; in contrast, the paths of ETNOs never get closer than that of Pluto. If most of the known ETNOs are experiencing Kozai episodes of the type that characterises the evolution of this comet, the associated orbital signature would resemble what is currently observed in the trans-Plutonian region. In addition, such scenario may explain naturally how objects originally located beyond 100 au can eventually reach the trans-Neptunian region or even the realm
Figure 7. Aphelion distance, $Q$, panels D, E and F (of Fig. 1) restricted to the time interval (-10, 10) kyr. For this object, when the eccentricity is at its highest, the inclination is at its lowest, and the argument of perihelion is close to 0°. In addition, its $Q$ librates around the value of Jupiter’s own aphelion, thick curve, not perihelion, thin curve.

Figure 8. The $e_i/e_\omega$-portrait for comet 96P/Machholz 1 relative to Jupiter during the time interval (-50, 0) kyr for the nominal orbit in Figs 1 and 2. The $e_i/e_\omega$-values for the ETNOs (see Table 1) are also plotted.

7 CONCLUSIONS

In this paper, we have studied the short-term dynamical evolution of orbital solutions similar to that of present-day comet 96P/Machholz 1 neglecting the effects of non-gravitational forces. This study has been carried out under the Newtonian and post-Newtonian approximations. In both cases, we have found that the evolution of these orbits is unlike that of any other members of the NEO population. Two rare evolutionary traits are observed: production of retrograde orbits and Kozai oscillations with zero argument of perihelion at minimum perihelion distance. The observed pathway towards the retrograde orbital domain joins the mechanism presented by Greenstreet et al. (2012) in providing suitable scenarios to produce retrograde NEOs and rocky, high-velocity meteoroids on equally retrograde orbits. Furthermore, comet 96P/Machholz 1 appears to be a good dynamical match to most known members of the ETNO population. It exhibits multiple properties that explain naturally the orbital distributions of these trans-Plutonian objects. The incarnation of the Kozai mechanism driving the evolution of comet 96P/Machholz 1 and studied here opens a new and unexpected window into the trans-Plutonian region that, if confirmed by the discovery of new members of the ETNO population exhibiting similar orbital features, can change our current views of the outermost Solar system. However, the hypothesis of the existence of one or more massive planets orbiting the Sun in nearly circular orbits so distant from Neptune is difficult to reconcile with the currently accepted cosmogonic paradigm. It remains to be tested if a Kozai scenario such as the one described here may work when the massive perturbers move in highly eccentric orbits, characteristic of scattered bodies (e.g. Bromley & Kenyon 2014).

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