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An Oort cloud origin for the high-inclination, high-perihelion Centaurs

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ABSTRACT

We investigate the origin of three Centaurs with perihelia in the range 15–30 au, inclinations above 70° and semimajor axes shorter than 100 au. Based on long-term numerical simulations we conclude that these objects most likely originate from the Oort cloud rather than the Kuiper belt or scattered disc. We estimate that there are currently between 1 and 200 of these high-inclination, high-perihelion Centaurs with absolute magnitude $H < 8$.

Key words: Kuiper belt: general – minor planets, asteroids: general – Oort Cloud.

1 INTRODUCTION

The Centaurs are a class of small objects wandering around the realm of the giant planets on unstable orbits. Typically, these objects have a semimajor axis of several tens of astronomical units (au) and their perihelion distance (q) is in the realm of the giant planets. From recent dynamical studies it is believed that the Centaurs originate from the Kuiper belt (KB) or scattered disc (SD) and form the bridge between these trans-Neptunian objects (TNOs) and the Jupiter-family comets (JFCs). This conclusion was motivated by dynamical studies demonstrating that TNOs regularly evolve on to Centaur orbits (Tiscareno & Malhotra 2003; Emel'yanenko, Asher & Bailey 2005; Di Sisto & Brunini 2007) and even all the way down to JFCs (Levison & Duncan 1997). One common element among all three studies is that the inclination (i) of the Centaurs tended to remain low: Tiscareno & Malhotra (2003) report a characteristic time-weighted mean Centaur inclination of 16°, while Emel'yanenko et al. (2005) and Di Sisto & Brunini (2007) find a comparable value. None of these studies recorded any Centaurs with $i > 60°$. Is this upper value in agreement with an origin in the TNO region? Brown (2001) computes the debiased inclination distribution for TNOs and suggests the functional form $\sin(i)\exp(-i^2/2\sigma^2)$, where $\sigma = 13° \pm 5°$. If the Centaurs originate from the TNO region then they should roughly retain the same inclination distribution. We can then compute the probability of finding a Centaur with $i > 60°$, i.e. $p(i > 60°)$, because it is just the complementary cumulative inclination distribution of the Centaur population. Using the nominal value for σ results in a probability $p(i > 60°) \sim 10^{-5}$. From this low value it is unsurprising that the above-mentioned studies did not record any Centaurs with $i > 60°$. It appears that for a Centaur to obtain an even higher inclination, an external agent is needed.

Given the very low probability for a Centaur originating from the TNO region to reach an inclination above 60° it is therefore surprising that to date there are 13 Centaurs with inclinations $i > 60°$, with six of them on retrograde orbits. The only known reservoir of small bodies that has many objects on high-inclination orbits is the Oort cloud (e.g. Dones et al. 2004), and thus it is probable that these high-inclination Centaurs originate from the Oort cloud and mimic its inclination distribution. If, instead, these high-inclination and retrograde Centaurs had originated from the TNO region, we should have detected tens of thousands of low-inclination Centaurs for every retrograde one. This is not the case and thus the presence of the high-inclination Centaurs indicates that there is an alternative source.

Several studies (Levison 1996; Wiegert & Tremaine 1999; Levison et al. 2006) have demonstrated that it is possible for Jupiter and Saturn to extract objects from the Oort cloud, and decrease these planetesimals' semimajor axis (a) to several tens of au. This works as follows: an Oort cloud object that passes through perihelion among the giant planets may experience an increase or decrease in its semimajor axis, depending on the closest approach distance to the planets and the latter's phasing at perihelion. This process repeats itself at roughly constant perihelion distance with random phasing. Eventually, a small number of objects will have their semimajor axis reduced sufficiently to become a Centaur. Thus, it is viable that the high-inclination and retrograde Centaurs with $q < 15$ au were either extracted and pulled in solely by Jupiter and Saturn, or they could have been decoupled by Uranus and Neptune and subsequently passed to Saturn and Jupiter which then pulled them all the way down to short semimajor axis. However, there are three objects that require further attention because all of these have $q > 15$ au and $i > 70°$. They are beyond the gravitational control of Saturn and thus fall into the domain of Uranus and Neptune. The orbital properties and absolute magnitude (H) of these three objects, taken from the Minor Planet Centre (MPC), are listed in Table 1. There is a potential fourth candidate, 2007 BP102, with semimajor axis $a = 23.9$ au, $q = 17.7$ au and $i = 64.8°$, but its observational arc is short and it is probably lost. Thus, we shall not include it.

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Table 1. Orbital data and absolute magnitude for the known high-inclination, high-perihelion Centaurs.

Designation	q (au)	a (au)	i (°)	Abs. mag. (H)
2002 XU93	20.9	66.6	77.9	8.0
2008 KV42	21.2	41.8	103.5	8.8
2010 WG9	18.7	53.8	70.2	8.1

One of these, 2008 KV42, is retrograde. Its dynamics was studied by Gladman et al. (2009) who suggested two scenarios for its origin: either it is at the extreme end of the inclination distribution of TNOs that have become Centaurs, or it points to a currently unobserved reservoir. Gladman et al. (2009) rule out the first scenario based on simulation data from Duncan & Levison (1997), who conclude that even though it is possible to obtain Centaurs with $i > 50°$, these are usually tied to Jupiter. Gladman et al. (2009) state that it is very difficult for Uranus and Neptune to decouple this object from Jupiter through a close encounter. The secular oscillations in eccentricity caused by perturbations from the giant planets are usually too small to directly reach Uranus from Jupiter. Gladman et al. (2009) do not mention whether or not this process could work for Centaurs pinned to Saturn, but once again the probability of a successful decoupling from Saturn by Uranus or Neptune is a rare event (Brasser & Duncan 2008). As stated earlier, Emel'yanenko et al. (2005) and Di Sisto & Brunini (2007) reported not witnessing any Centaur having an inclination above 60°.

A second mechanism Gladman et al. (2009) suggest is to extract the objects from the Oort cloud as their perihelia drift sunward under the influence of the Galactic tide. Gladman et al. (2009) correctly assess that this extraction is a difficult process because the semimajor axis needs to be reduced from over 1000 au to below 100 au while keeping $q > 15$ au at all times. In other words, the extraction needs to be performed by Uranus and Neptune alone, without the help of Saturn. Gladman et al. (2009) report not having come across this mechanism in the literature and thus rule it out. They suggest instead that an unobserved population of nearly isotropic objects resides not too far beyond Neptune and some of these objects have their perihelia decreased sufficiently by external factors that Neptune extracts them from this reservoir. Unfortunately, there is no observational evidence supporting this claim (Schwamb et al. 2010). Here, we show that these high-inclination, high-perihelion (HIHQ) Centaurs most likely originate from the Oort cloud and are decoupled and pulled down only by Uranus and Neptune. In other words, there is only one dynamical pathway for high-inclination Centaurs with $q > 15$ au rather than the two mentioned above for objects with $q < 15$ au. We demonstrate that the Oort cloud will only dominate as a source once the inclination is above a certain value where contribution from the TNO region becomes unimportant.

Our study has a few similarities with Kaib et al. (2009). They investigated the origin of the Centaur 2006 SQ372, an object with heliocentric $(a, q, i) = (1057, 24.1, 19.^{\circ}5)$. Through numerical simulations they compare the production rates of objects like SQ372 from both the SD and the Oort cloud and conclude that SQ372 most likely originated from the inner Oort cloud ($a \lesssim 20\,000$ au) rather than the SD. Additionally, they state that the Oort cloud most likely dominates the production of Centaurs with large semimajor axis ($a \gtrsim 500$ au), irrespective of inclination. This was also reported in Emel'yanenko et al. (2005).

Before we continue, we want to point out that there is no universally accepted definition of what a Centaur is in terms of its orbital properties. The MPC defines Centaurs as having a perihelion distance beyond the orbit of Jupiter and a semimajor axis shorter than that of Neptune; this classification was also adopted by Gladman, Marsden & Vanlaerhoven (2008), but they added the additional constraint that $q > 7.35$ au. However, the Jet Propulsion Laboratory (JPL) classification requires that the semimajor axis is between those of Jupiter and Neptune. Objects that have q in the region of the giant planets but semimajor axis larger than that of Neptune are classified as 'SD' objects by Gladman et al. (2008). While this nomenclature may make sense based on dynamical considerations, we find that the semimajor axis restriction makes classification more complicated because of the objects' inherent increased mobility in a versus q for very eccentric orbits. Thus, for this study, we adopt the traditional definition that a Centaur is a planetesimal whose perihelion distance is in between the orbits of Jupiter and Neptune, i.e. $q \in (a_J, a_N)$, without a restriction on semimajor axis. This definition is also used by Tiscareno & Malhotra (2003), Emel'yanenko et al. (2005) and Di Sisto & Brunini (2007). All objects with $q > a_N$ that are not in the Oort cloud ($a \lesssim 2000$ au) we refer to as TNOs, at times isolating the KB or SD.

This paper is organized as follows. In the next section, we describe our numerical simulations. In Section 3, we present the results from these simulations. In Section 4, we derive how many HIHQ Centaurs with absolute magnitude $H < 8$ we expect to exist and in the last section we draw our conclusions.

2 METHODS: NUMERICAL SIMULATIONS

In order to test whether the HIHQ Centaurs originate from the Oort cloud or the SD, we performed a large number of numerical simulations divided into several categories. Specifically, we ran a total of four sets of simulations: two pertaining to the evolution of the TNO region and two dealing with the Oort cloud.

The first set of simulations come from Lykawka et al. (2009) and were used to determine whether or not the TNO region could be the dominant source of the HIHQ Centaurs. These simulations were integrated using the MERCURY package (Chambers 1999) and lasted for 4 Gyr with the giant planets on their current orbits. The time step was 0.5 yr. The simulation contained 280 000 massless test particles initially placed on Neptune-crossing orbits with $a = 30$–50 au, $q = 25$–35 au and $i < 20°$. Data were output every 10 kyr and particles were removed when they hit a planet or were farther than 1000 au from the Sun.

A second set of simulations to measure the contribution from the TNO region was performed. However, unlike the simulations of Lykawka et al. (2009), where the giant planets were placed on their current orbits, these simulations pertain to the evolution of the trans-Neptunian region over 4 Gyr in the framework of the Nice model (Gomes et al. 2005; Tsiganis et al. 2005). The results of these simulations shall be discussed in detail in a forthcoming paper. Briefly, these simulations consist of five separate simulations starting with 5000 test particles each and the giant planets in a more compact configuration. The planets are then evolved through the 'jumping Jupiter' evolution of Brasser et al. (2009) using the interpolation method of Petit, Morbidelli & Chambers (2001). Once the planets had settled down, we cloned all remaining test particles with heliocentric distance $r < 3000$ au 10-fold by applying a random variation in the mean anomaly with magnitude 10^{-6}. Each simulation had approximately 15 000 test particles. The simulations were continued for 10 Myr to allow the planets to reach their current orbits adiabatically and we refer to Morbidelli et al. (2010) for a more detailed description of this process. Once the planets had reached their current orbits, we spread all simulations over 10 CPUs to hasten the evolution. We continued the simulations to 500 Myr, 2, 3 and 4 Gyr, cloning the remaining test particles 10-fold at each of these times except at 4 Gyr. The time step was 0.4 yr and particles were removed either when they were farther than 3000 au from the Sun or when they came within 3 $R_\odot$ or hit a planet. The terrestrial planets were not included. Data were output every Myr. However, during the last Gyr of the simulation the data were written every 0.1 Myr. We used data from the last Gyr of these simulations to compute the contribution of the TNO region to the HIHQ Centaur region.

We determined whether or not the Oort cloud is a feasible mechanism to generate HIHQ Centaur objects by running a third set of numerical simulations. We took the Oort cloud objects from Brasser et al. (2012), who studied the formation of the Oort cloud while the Sun was in its birth cluster. We cloned each Oort cloud object 10×times at the beginning of the simulations by randomizing the three angles: longitude of the ascending node (Ω), argument of perihelion (ω) and mean anomaly (M). We believe that this procedure is justified because the phases of the planetesimals with respect to the Galactic tide are essentially random when the Sun's birth cluster evaporates. The Oort cloud that formed in these simulations has an inner edge at approximately 500 au and the outer edge is at about 100 000 au. We ran two sets of 40 simulations with approximately 30 000 test particles in each (total of the order of 2.5 million). One set of data was taken from the Hernquist clusters of Brasser et al. (2012) while the other set used data from the Plummer clusters. We simulated the evolution of the objects in the cloud for 4 Gyr under the influence of the Galactic tide and passing stars. The tides were implemented using the method of Levison, Dones & Duncan (2001) with a Galactic density of 0.1 $M_\odot$ pc^{-3} (Holmberg & Flynn 2000) and Galactic rotational velocity of 30.5 km s^{-1} kpc^{-1} (McMillan & Binney 2010). The perturbations from passing stars were included as described in Heisler, Tremaine & Alcock (1987) with the stellar spectral data and velocity of García-Sánchez et al. (2001). We simulated these objects using *Swift* RMVS3 (Levison & Ducan 1994) without the giant planets. Particles were removed when they came closer to the Sun than 38 au or when they were farther than 1 pc from the Sun. These simulations allowed us to determine which objects potentially reached the giant planets and which ones stayed in the inner Oort cloud for the age of the Solar system. The time step was 50 yr. On average, 7 per cent of all the planetesimals in the inner Oort cloud came closer to the Sun than 38 au in 4 Gyr. The latter planetesimals were kept and re-integrated from the beginning with the giant planets present on their current orbits while the other planetesimals were discarded. Thus, each simulation contained approximately 2500 test particles (total approximately 200 000). We used SCATR (Kaib, Quinn & Brasser 2011), instead of *Swift* RMVS3, for speed. In SCATR the barrier between the heliocentric and the barycentric frame was set to 300 au, the time step inside the barrier was once again 0.4 yr and outside it was 50 yr. The Galactic tide and passing stars were included.

A last, fourth set of simulations were similar to the third set apart from the fact that the classical Oort cloud was used, i.e. the Oort cloud that was formed in the current Galactic environment rather than during the Sun's birth cluster (e.g. Dones et al. 2004). These simulations were performed to determine whether the classical Oort cloud could dominate the inner Oort cloud as the source of HIHQ Centaurs. The data were taken from Brasser, Higuchi & Kaib (2010) at 250 Myr and simulated for the remaining 3.8 Gyr. We chose this early time because Brasser et al. (2010) have shown that the median time to form the Oort cloud is of the order of a couple of hundred Myr. In the current environment the formation of the inner Oort cloud takes longer, of the order of 1 Gyr (Dones et al. 2004). However, this reservoir is modelled with the third set of simulations reported above and here we are only interested in production from the outer Oort cloud ($a \gtrsim 20\,000$ au), most of which has formed in less than 100 Myr. Only particles that were already in the Oort cloud were used. Once again, the Galactic tide, passing stars and the planets were included. Once again, we used SCATR with the same parameters as above.

3 RESULTS

In this section the results from our numerical simulations are presented.

3.1 Probability and critical inclination

The probability of finding a HIHQ Centaur is essentially given by the fraction of particles that ever enter the HIHQ Centaur phase multiplied by the particle's fractional lifetime in the HIHQ Centaur state. For TNO simulations the data were averaged over the last 500 Myr while for the Oort cloud simulations the data were averaged over the last 1 Gyr. Outputs from simulations within each set were combined together to improve statistics. The typical number of data points (number of particles at each output multiplied by the number of outputs) was in millions.

Using the TNO simulations from Lykawka et al. (2009) (set 1) and the ones from set 2, we computed the probability of a body being in the HIHQ Centaur state. The probability for HIHQ Centaur production turned out to be 1–2 × 10^{-5} for objects with $q \in [15, 30]$ au, $a < 100$ au and $i > 65^\circ$. This value is almost the same for both sets of simulations (1 and 2). The similar order of probabilities for HIHQ Centaurs with $i \gtrsim 65^\circ$ even for different early Solar system architectures and evolution of the planets suggests that the results are generally robust for Neptune-encountering small bodies. Hence the details of the simulations (migration versus no migration) and the type of integrator that was being used (MERCURY versus *Swift* RMVS3) seem to play a minor role in determining the intrinsic probabilities for a typical TNO source. From the simulations of both the inner and classical Oort cloud (3 and 4) we also obtained a probability of $\sim 10^{-5}$ for an Oort cloud object to obtain a HIHQ Centaur with $i > 65^\circ$. This agreement in the production probability between objects from the inner and classical Oort cloud suggests that the probability estimate is robust. These results would suggest that at 65° inclination both reservoirs contribute approximately equally, and that we need to go to higher inclinations to determine whether or not one source dominates over the other. In other words, we need to determine if there is a critical inclination.

In principle the probability of finding a HIHQ Centaur from the TNO region is the product of the probability that a TNO becomes a Centaur with $q \in [15, 30]$ au and $a < 100$ au (approximately 1 per cent) and the complementary cumulative inclination distribution, $p(> i)$. A similar argument applies to Oort cloud objects. Fig. 1 plots the probability of obtaining a HIHQ Centaur from both the TNO region and the Oort cloud as a function of inclination. The change of slope in the TNO profile at 60° is caused by a sample of Centaurs in resonance with Neptune which only became unstable towards the end of the simulation. However, it does not severely affect the general outcome since all the objects we consider in this study have higher inclinations. The shaded region takes into account the observed population ratio between the Oort cloud and SD, which appears to be between 100 and 1000 (Duncan & Levison 1997). As one can see, if this population ratio is representative of the reality

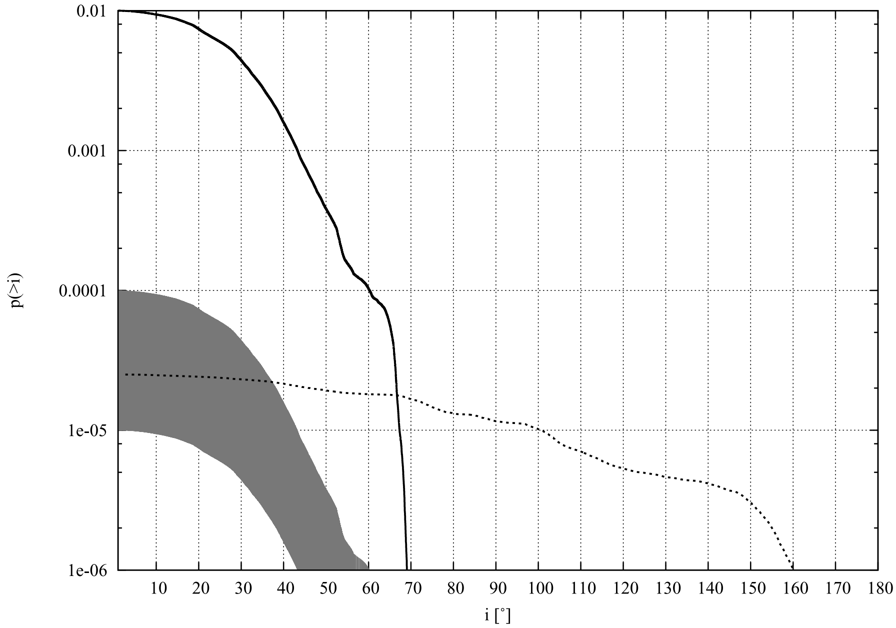

Figure 1. Plot of the probability of finding a HIHQ Centaur as a function of inclination, $p(>i)$. The thick line corresponds to HIHQ Centaurs originating from the TNO region while the dashed line is for an Oort cloud source. The shaded region corresponds to a TNO source if the Oort cloud to SD population ratio is taken into account.

then the Oort cloud should dominate Centaur population production with $q \in [15, 30]$ and $a < 100$ when $i \gtrsim 40^\circ$, but it could be at a much lower inclination. However, the Oort cloud to SD population ratio is still an open problem and thus the above results should only be used as indicative rather than absolute. Instead we focus on the first curve, which meets the Oort cloud probability at a critical inclination $i_c \sim 65^\circ$. Thus it is almost certain that HIHQ Centaur production is dominated by the Oort cloud when the inclination $i > i_c$, irrespective of the Oort cloud to SD population ratio.

In this study we peg the value of the critical inclination at 70° and we assume that Centaurs with higher inclinations are exclusively provided by the Oort cloud. This assumption is justified given the results of Fig. 1. All three of the objects in our sample have an inclination $i > 70^\circ$ and approximately 1 in 10^5 Oort cloud objects are in the HIHQ Centaur state at any time.

3.2 Extraction from the Oort cloud to a HIHQ Centaur

The evolution of Oort cloud objects towards the HIHQ Centaur state is straightforward. Two examples are given in Fig. 2. The top panels depict the semimajor axis and perihelion distance with time. The horizontal lines indicate the positions of the giant planets, which are indicated by the labels. The bottom panels depict the evolution of the inclination of these two objects. The inclinations of the three known objects are indicated by the horizontal lines.

As one can see from the top panels, the perihelion distance of the object decreases on Gyr time-scales. Once it is in the vicinity of Neptune, encounters with this planet reduce the semimajor axis of the object on a time-scale of several hundred Myr. This lowering of the semimajor axis should occur faster than the time it takes for the Galactic tide to decrease the perihelion past Uranus down to Saturn. The Galactic tide causes perturbations that decrease the perihelion according to $\dot{q} \propto a^2$ (Duncan, Quinn & Tremaine 1987). This scaling suggests that Oort cloud objects with an initial semimajor axis longer than some maximum value, $a_{\max}$, pass by Uranus and Neptune too quickly for these planets to have the time to extract them from the cloud. From our simulations we found $a_{\max} \sim 20\,000$ au, with a median initial semimajor axis of ∼3200 au if the main source is the inner cloud, or ∼7000 au if the classical cloud dominates. These values are in rough agreement with those reported in Kaib et al. (2009). The discontinuity in q in the plots at 1.4 Gyr is caused by a close stellar passage and has no bearing on the overall outcome of our simulations.

For a long time the perihelion of both objects is pinned to Uranus with short-period oscillations superimposed on it caused by the Kozai mechanism (Kozai 1962), similar to the current evolution of the three known objects. The two fictitious objects depicted above stay in the HIHQ Centaur state for about 1 Gyr. We find that, on average, an Oort cloud object resides in the HIHQ Centaur phase for 200 Myr, which was obtained by measuring the total time each HIHQ Centaur resided in this phase and dividing by the total simulation time or lifetime of the particle. This typical residence time is consistent with that found by Gladman et al. (2009) for the evolution of 2008 KV42 and Kaib et al. (2009) for SQ372. In Fig. 2 we chose these longer lived cases for illustrative purpose only.

3.3 Inclination and perihelion distribution

A natural question to ask is what are the long-term inclination and perihelion distributions of these objects. We have computed these distributions by recording the inclination and perihelion distance of each object in the HIHQ Centaur state at each output interval in our simulations. The steady-state inclination and perihelion distributions are depicted in Fig. 3. The distributions are normalized such that the sum of the bins is unity. The median inclination is 104.°6 and the median q is 22 au. As can be seen the majority of objects should have their perihelion near Uranus. Approximately 20 per cent of objects have $i \in [100^\circ, 110^\circ]$, exactly where 2008 KV42 was found. The other two objects, 2010 WG9 and 2002 XU93, are in the first bin. In fact, all three objects are found in the region where the model predicts most objects should be.

Now that we have shown the mechanism behind the production of HIHQ Centaurs from the Oort cloud, and what the expected

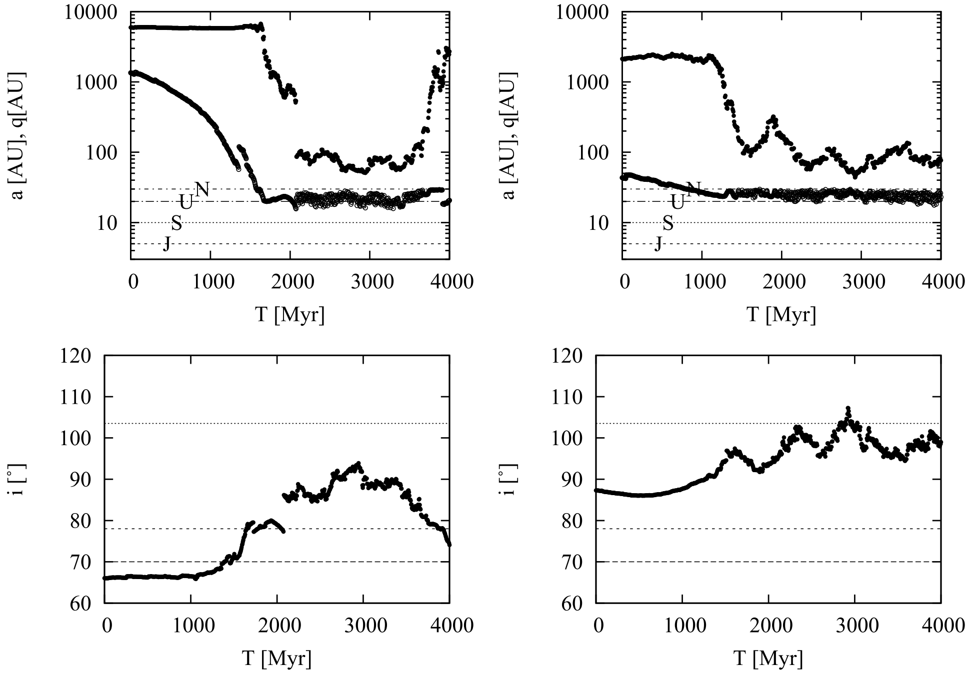

Figure 2. Top panels: evolution of the semimajor axis and perihelion of two inner Oort cloud objects towards the HIHQ Centaur state. Bottom panels: the evolution of the inclination for both objects.

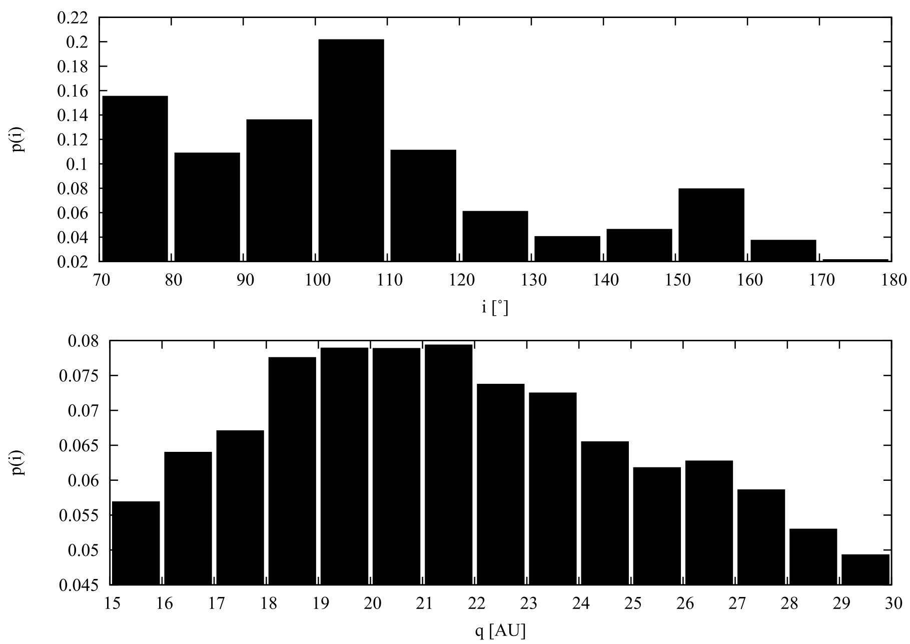

Figure 3. Top panel: the steady-state inclination distribution of the HIHQ Centaurs. Bottom panel: the steady-state perihelion distribution of the HIHQ Centaurs.

perihelion and inclination distribution of these objects are, we proceed to estimate how many HIHQ Centaurs there could be.

4 IMPLICATION: NUMBER OF HIHQ CENTAURS AND OORT CLOUD OBJECTS

We can use the dynamics of the Oort cloud to estimate how many HIHQ Centaurs we would expect. Brasser (2008) suggested that the Oort cloud formed in two stages: the first state would occur while the Sun was in its birth cluster, at the time just after the formation of Jupiter and Saturn, when the gas from the primordial solar nebula was still present. The second stage would occur some 600 Myr later, at the time of a dynamical instability of the giant planets, which is thought to have coincided with the Late Heavy Bombardment (LBH) of the terrestrial planets (Gomes et al. 2005; Tsiganis et al. 2005). Thus the Oort cloud is a mixture of bodies from two sources and as we demonstrated above, the HIHQ Centaurs can originate from both the inner and classical clouds. This means we cannot isolate one source from the other.

Unfortunately, we have very little information about the size distribution and total mass of the planetesimals that formed the first stage of the Oort cloud, apart from the fact that the total mass scattered by Jupiter and Saturn may have been much more than during the second stage (e.g. Thommes, Duncan & Levison 2003; Levison, Thommes & Duncan 2010). However, we know much more about the size distribution and total mass during the second stage. Thus we shall focus on the second stage first.

Morbidelli et al. (2009) claim that there were approximately 10^8 objects in the trans-Neptunian disc at the time of the LHB with $H < 8$, assuming that all these objects had an albedo of 4.5 per cent. Taking a 3 per cent efficiency for Oort cloud formation in the current Galactic environment (Dones et al. 2004; Kaib & Quinn 2008) implies that there are at least 3×10^6 Oort cloud objects with $H < 8$, and therefore we expect at least 30 HIHQ objects of the same size.

An alternative estimate is obtained as follows, but this is only applicable to the inner Oort cloud and/or if the inner cloud is the dominant source of HIHQ Centaurs. Schwamb et al. (2010) argue that there are between 112^{+423}_{-71} and 595^{+1949}_{-400} Sedna-like objects in the inner Oort cloud with semimajor axes $a < 3000$ au for objects whose size distribution follows the cold and hot population Kuiper belt objects (KBOs), respectively (Fraser, Brown & Schwamb 2010). The error values correspond to 95 per cent confidence levels. The latter value could be problematic because the low formation efficiency of Brasser et al. (2012) would suggest that there were more than 30 000 Sedna-sized bodies in the disc, and thus its total mass should have been several hundred Earth masses. Nevertheless, we shall use this estimate in our derivation below.

We take the cumulative slope in absolute magnitude of KBOs from Fraser et al. (2010), which is $\alpha = 0.82$ for the cold KBOs and $\alpha = 0.35$ for the hot KBOs, and assume that the size distribution of bright KBOs applies to objects with the same size as the HIHQ Centaurs. The absolute magnitude of Sedna is 1.6 (Brown, Trujillo & Rabinowitz 2004) and thus the number of objects in the inner Oort cloud with $H < 8$ ranges from $1.1^{+5.0}_{-0.7} \times 10^5$ if $\alpha = 0.35$ to $2.0^{+9.0}_{-1.5} \times 10^7$ if $\alpha = 0.82$. With a production probability of 10^{-5}, the nominal number of HIHQ Centaurs with $H < 8$ is expected to range from 1 to 200. The former value is too low since more objects have already been found and the sample is far from being observationally complete. The highest value is also problematic for reasons discussed earlier: too much mass had to exist in the primordial disc and be deposited in the inner Oort cloud. Thus, we believe that the current number of HIHQ Centaurs is probably in between these two extremes. In any case the direct link between the HIHQ Centaurs and the Oort cloud could be used to constrain Oort cloud formation models and possibly infer the mass and size of the primordial solar nebula once more HIHQ Centaur objects are discovered.

5 CONCLUSIONS

We have analysed the origin of several Centaurs with inclinations above 70°, perihelia between 15 and 30 au and semimajor axes shorter than 100 au. We call this population the HIHQ Centaurs. The high inclination of these objects, including one retrograde, suggests an origin from the Oort cloud, where the Galactic tide is capable of substantially modifying the original inclination. We find that for inclinations higher than 70° the Oort cloud dominates as a source over the regular TNO region, which consists of the KB and SD, although this transition could occur at a much lower inclination, depending on the Oort cloud to SD population ratio. The steady-state probability of any Oort cloud object residing on a HIHQ Centaur orbit is 10^{-5}. Based on this probability, and using the typical formation efficiency of the Oort cloud and the expected number of objects to reside in the source region, we predict that there are between 1 and 200 HIHQ Centaurs with $H < 8$. Apart from Sedna and new comets, we propose that the HIHQ Centaurs are the only directly visible objects that can be used to constrain the number of Oort cloud objects once they are observationally complete.

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