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Centaurs from the Oort cloud and the origin of Jupiter-family comets

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ABSTRACT

A numerical study of an ensemble of orbits based on observed objects in the near-Neptune high-eccentricity (NNHE) region, with perihelion distances q in the range $28 < q < 35.5$ au and semimajor axes a in the range $60 < a < 1000$ au, is used to predict the orbital distribution of Centaurs ($5 < q < 28$ au) for comparison with observations after correcting for discovery biases. The majority of Centaurs produced in this way have $a \lesssim 60$ au. However, the intrinsic number of observed Centaurs is dominated by longer period objects, the number with $a > 60$ au being roughly an order of magnitude greater than that for $a < 60$ au, and therefore inconsistent with a source in the NNHE region, which is broadly similar to the so-called 'Scattered Disc'. The observed distribution of Centaurs with $a \lesssim 60$ au is also inconsistent with this source, although it is conceivable that in this region the discrepancies might be explained by factors such as out-gassing, splitting or varying albedo not included in our model. Thus, although Centaurs can be produced from the NNHE region, their numbers and orbital distributions are inconsistent with this region being the dominant source for all Centaurs. We conclude that there must be another source flux, especially for the longer period, more populous group, and suggest that the most likely source for these objects is the Oort cloud. Thus, there are two separate, but overlapping, dynamical classes of Centaurs, one originating from the Oort cloud and the other from the NNHE region. The two source regions produce roughly similar contributions to Centaurs with $a \lesssim 60$ au and to the observed Jupiter family of comets.

Key words: celestial mechanics – comets: general – Kuiper Belt – minor planets, asteroids – Oort Cloud – Solar system: formation.

1 INTRODUCTION

Centaurs represent an observed population of sizable asteroids or cometary nuclei circulating largely between the orbits of Jupiter and Neptune and usually crossing the orbit of at least one giant planet (e.g. Jedicke & Herron 1997; Larsen et al. 2001). The prevailing opinion is that these small bodies have been captured from the trans-Neptunian region (e.g. Horner et al. 2003; Tiscareno & Malhotra 2003) and are a transition population en route to becoming Jupiter-family (JF) comets or being dynamically ejected to interstellar space. This picture has arisen as a result of various numerical simulations that have elaborated the detailed dynamical pathways connecting different zones of the outer Solar system (e.g. Hahn & Bailey 1990; Duncan & Levison 1997; Levison & Duncan 1997; Morbidelli 1997; Tiscareno & Malhotra 2003; Horner, Evans & Bailey 2004a,b; Emel'yanenko, Asher & Bailey 2004). In this paper we call 'Centaurs' all such bodies with perihelion distances q in the range $5 < q < 28$ au without regard to semimajor axis a or inclination i. For completeness, we note that we exclude from this definition the satellites of the outer planets, the few Plutinos (objects in the 2 : 3 mean-motion resonance with Neptune) and other stable resonant objects that may lie in this zone, and Oort cloud comets. It is particularly difficult to define a unique orbital classification for Centaurs, because some of these objects, for example Oort cloud comets, can evolve from one class to another.

Considering Centaurs as the proximate source of JF comets, it seems relevant to note that non-resonant orbits in the so-called 'classical' Edgeworth–Kuiper belt (EKB) cannot be the dominant source of JF comets. The classical belt is the region beyond Neptune containing objects largely of low inclination and semimajor axes $a \lesssim 50$ au. First (see Fig. 1), apart from resonant objects (classes P and R as defined by Emel'yanenko, Asher & Bailey 2003) there are no known objects in this region with well-determined orbits and q close to Neptune's orbit. Secondly, there are several known objects of larger a and much higher eccentricity with q close to Neptune's orbit (Emel'yanenko et al. 2004). Thirdly, such Neptune approaching or 'Scattered Disc' orbits are a much more efficient source of JF comets than the classical EKB (Duncan & Levison 1997; Malhotra, Duncan & Levison 2000). The same argument would

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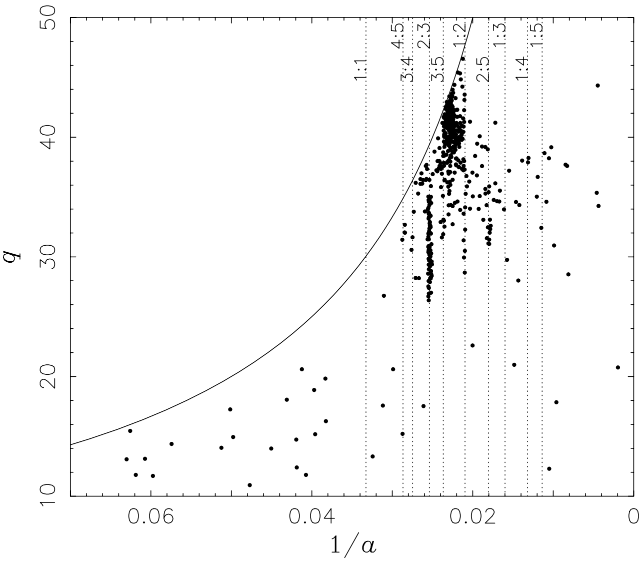

Figure 1. Observed distribution of multiple-opposition TNOs and Centaurs (2005 February). The solid curve shows the locus of objects of zero eccentricity. Dotted lines show the principal mean-motion resonances with Neptune. Note the absence of non-resonant objects with q close to the orbit of Neptune and $a \lesssim 50$ au.

suggest that Centaurs from the so-called Scattered Disc dominate those produced, if any, from the EKB, and therefore that the near-Neptune high-eccentricity (NNHE) region could also be a dominant source of Centaurs.

Thus, as a transition population, whether they are viewed as 'escapees' from the Kuiper belt (Stern & Campins 1996), which seems unlikely (at least for the majority of Centaurs), or come from another source, Centaurs play a pivotal role in our understanding of the origin of JF comets and the structure of the outer Solar system. In particular, their orbital distribution provides important constraints on possible solutions to these questions.

This paper evaluates the predicted orbital distribution of Centaurs originating from the NNHE region, with $28 < q < 35.5$ au and $60 < a < 1000$ au, and compares it with a debiased distribution of Centaurs derived from observations. We show that there are two overlapping classes of these bodies: a dominant class that contains mostly long-period orbits ($a \gtrsim 60$ au), and a much less populous class containing objects mostly having $a \lesssim 60$ au. The dominant class probably originates from source orbits in the Oort cloud and contains a 'tail' of objects extending to $a < 60$ au, roughly comparable in numbers to the total number of objects in the second class. The latter may originate largely from the NNHE region.

Our principal conclusion is that there are two classes of Centaurs and that the majority originate from the Oort cloud. This suggests that there should be two corresponding classes of JF comets, a result which remains to be tested by physical observations.

2 EVOLUTION OF CENTAURS FROM TRANS-NEPTUNIAN ORBITS

Emel'yanenko et al. (2004) investigated the dynamical evolution of seven trans-Neptunian objects (TNOs) with $28 < q < 35.5$ au and $60 < a < 1000$ au, occupying the NNHE region. A bundle of 250 cloned orbits for each object was integrated forwards for the age of the Solar system, and the results weighted according to each object's initial orbital elements, size and discovery circumstances in order to provide predicted orbital distributions for comparison with observations of JF comets and Centaurs. In the present paper, we use these calculations to determine the intrinsic orbital distribution of Centaurs originating from the NNHE region.

The majority of Centaur half-lives are extremely short compared to the age of the Solar system (Dones, Levison & Duncan 1996; Tiscareno & Malhotra 2003; Horner, Evans & Bailey 2004a). It is therefore possible to determine their quasi-steady-state orbital distribution by considering the orbital properties of objects transferred from the NNHE region to the smaller q Centaur zone ($5 < q < 28$ au) during a relatively short time interval near the present epoch. Figs 2, 3 and 4 show the normalized a, q and i distributions obtained during the first 100 Myr of orbital evolution from the NNHE region with the appropriate weighting. These distributions show that the majority of Centaurs from the NNHE region have $20 < a < 60$ au,

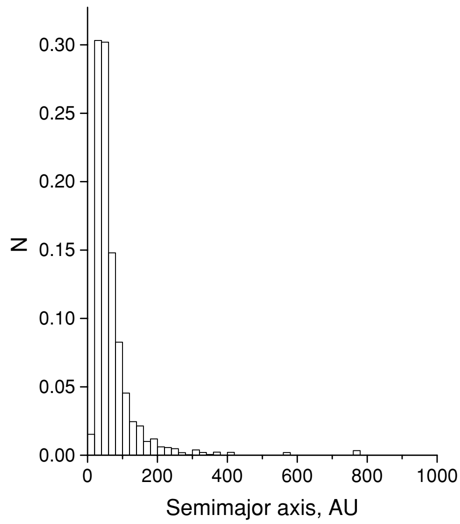

Figure 2. The predicted a distribution for Centaurs captured from the NNHE region over 100 Myr. N denotes the fraction of objects lying in each bin of the histogram.

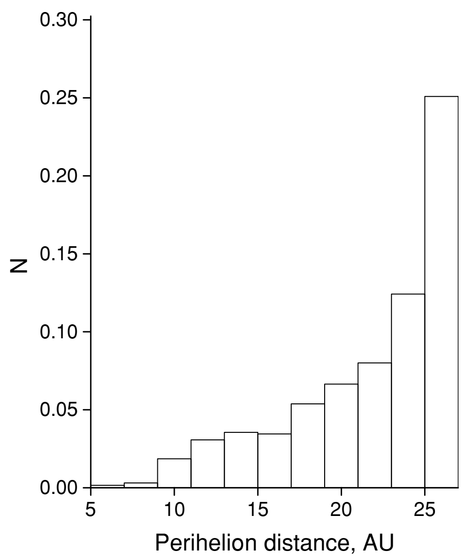

Figure 3. The steady-state q distribution for Centaurs captured from the NNHE region over 100 Myr.

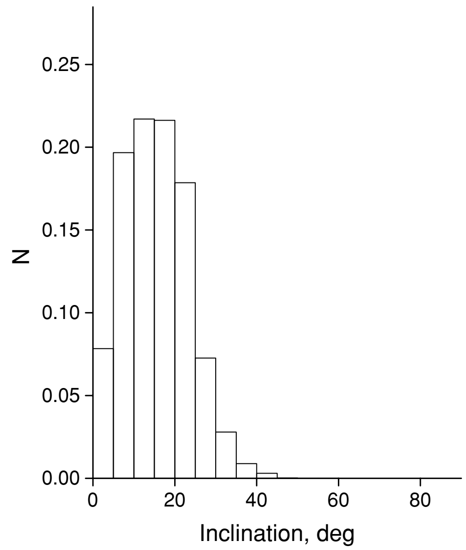

Figure 4. The steady-state i distribution for Centaurs captured from the NNHE region over 100 Myr.

numbers that increase with increasing q, and a span of inclinations similar to the initial range, with a mean value of around 16°.

Although the details of this procedure involve some uncertainties (for example, the assumed initial NNHE orbital distribution, which depends on a rather small observational sample), we have found that the main dynamical features are rather stable. For example, almost the same normalized orbital distributions are obtained for each individual object in our initial sample, and the corresponding histograms determined from integrations extending over 4.5 Gyr are also qualitatively the same. Thus, these figures represent a robust prediction of the orbital distributions of Centaurs originating in the NNHE region.

The results also show that the ratio of the steady-state number of captured Centaurs to the number of objects in the NNHE source region is approximately 0.008 for the time interval 50–150 Myr, and about 0.01 for the whole time interval (4.5 Gyr), i.e. nearly the same. Thus, if there are 10^{10} comet-sized objects in the NNHE region (Trujillo, Jewitt & Luu 2000; Emel'yanenko et al. 2004; Fernández, Gallardo & Brunini 2004) we should expect approximately 8×10^7 Centaurs, roughly 2/3 of which would have $a \lesssim 60$ au (Fig. 2).

3 COMPARISON WITH OBSERVATIONS

3.1 Debiasing procedure

In order to compare the predicted Centaur orbital distributions with those observed, we selected multiple-opposition Centaurs from the lists of the Minor Planet Center.[1] We included all objects with $5 < q < 28$ au except those in the 2 : 3 resonance with Neptune. In 2004 October we found 42 such Centaurs.

Each observed object represents a sample drawn from a population having a range of orbital parameters and sizes, and consequently having different chances of discovery. We allow for these observational biases by adopting a similar procedure to that developed by Emel'yanenko et al. (2004) for high-eccentricity TNOs. Each discovered object with orbital elements $\boldsymbol{E}$ and apparent magnitude m at discovery has a weight w proportional to $1/(p_1 p_2 p_3)$, where p_1 is the probability that it falls in an area of sky accessible to the relevant field of surveys, p_2 is the probability that it has an apparent magnitude m when in such a field, and p_3 is the probability that an object of that apparent magnitude will be discovered.

There are a number of observational differences between the case of Centaurs and high-eccentricity TNOs, and so we have slightly modified our previous methods for computing p_1, p_2 and p_3. First, the range of ecliptic latitude, β, for discovered Centaurs is slightly larger than that for TNOs, although $|\beta|$ for the majority of discovered Centaurs is still less than 5°. For this reason, we regard the field of surveys as comprising the range $|\beta| < 5°$, and model only those Centaurs having $|\beta| < 5°$ at the time of discovery (33 objects).

A further complication is that the orbits of Centaurs can be more circular than those of high-eccentricity TNOs, allowing them to remain in the discoverable region for a longer time owing to their lower orbital speeds near perihelion. The product $p_1 p_2$ has therefore been calculated numerically. We divide the orbital period into 10 000 equal time-steps, and calculate p_2 for each small interval in the field of surveys using the method described by Emel'yanenko et al. (2004). Summing these probabilities in the range $|\beta| < 5°$, we estimate the product $p_1 p_2$.

Finally, the average size of Centaurs is smaller than that of discovered TNOs. There are some indications (e.g. Bernstein et al. 2004) that the differential size distribution of Centaurs and TNOs is a power law of constant slope $-q'$ only for the largest objects. Therefore, in order to estimate p_3, we use data only for the largest multiple-opposition TNOs and Centaurs, i.e. those with absolute magnitudes $H < 8$. Assuming the canonical value $q' = 4$ (Jewitt, Luu & Trujillo 1998; Gladman et al. 2001; Trujillo, Jewitt & Luu 2001), the approximation $p_3 \propto \exp(-m/1.67864)$ is valid for $15.75 < m < 24.25$.

3.2 Results

The debiased distributions of a, q and i for observed Centaurs are shown in Figs 5, 6 and 7, calculated by assuming $q' = 4$. Varying q' (e.g. by ± 1) does not qualitatively alter these results, which are noticeably different from those obtained above for objects evolving

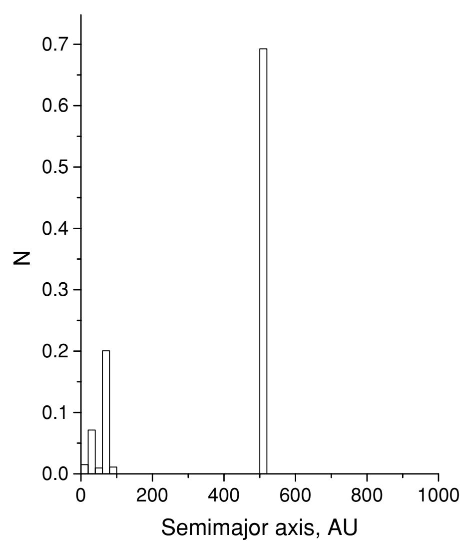

Figure 5. The debiased a distribution for observed Centaurs.

[1] See http://cfa-www.harvard.edu/iau/lists/TNOs.html, and http://cfa-www.harvard.edu/iau/lists/Centaurs.html.

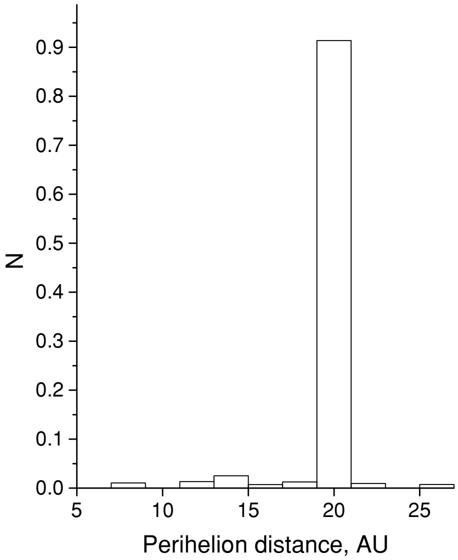

Figure 6. The debiased q distribution for observed Centaurs.

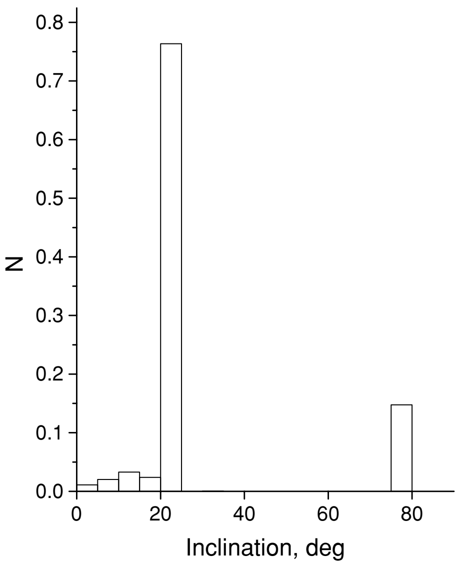

Figure 7. The debiased i distribution for observed Centaurs.

from the NNHE region. There is no doubt that the abrupt changes in Figs 5–7 are caused by a relative lack of statistical data. We show these histograms only to illustrate the present state of observations, which we discuss below.

The main differences are associated with objects having $a > 60$ au. Although only a few such objects contribute to the observed distributions, the very low discovery probabilities of such long-period objects suggest that they must represent a much larger population (cf. the case of the TNO 15874 = 1996 TL_{66}; Luu et al. 1997). In particular, the presence of two objects with large weights, namely 2000 OO_{67} ($a = 514$ au, $q = 20.8$ au, $i = 20\overset{\circ}{.}1$) and 2002 XU_{93} ($a = 67.4$ au, $q = 21.0$ au, $i = 77\overset{\circ}{.}9$), leads to the 'spikes' in Figs 5–7. With the caveat noted above, the data are incompatible with the hypothesis that the majority of Centaurs ($5 < q < 28$ au) come from the NNHE region.

A further important point is that the intrinsic number of observed Centaurs (the majority of which have $a > 60$ au) is approximately 0.13 times the intrinsic number of observed objects in the NNHE region. This ratio is much larger than the corresponding value (0.008) predicted by our numerical integrations. We therefore conclude that the majority of Centaurs with $a > 60$ au cannot originate from the NNHE region.

Moreover, further differences exist between the simulated and observed distributions, even for the region $a < 60$ au. First, as shown in Fig. 5, only 10 per cent of all Centaurs with $a < 60$ au have $40 < a < 60$ au. This is much smaller than the corresponding value (approximately 50 per cent) found for the simulated distribution shown in Fig. 2. Secondly, in contrast to Fig. 3, there is no systematic increase in the number of Centaurs versus q, the 'spike' in Fig. 6 being caused by two objects with $a > 60$ au. These points also suggest that the NNHE region makes only a relatively small contribution to the observed Centaurs with $a < 60$ au.

We have made many attempts to overcome these discrepancies by changing the values of q' and p_3 within reason, but without success. If q' decreases, there are fewer objects with smaller sizes, and because smaller objects are preferentially discovered nearby, a given number of discoveries in the observed population would imply an increase in the fraction of Centaurs at closer distances in the debiased distribution.

Therefore, increasing (or respectively decreasing) q' will tend to improve (or worsen) the match between the simulated and observed q distributions. However, even increasing q' to 5 or 6 does not improve the agreement sufficiently. Moreover, there are some observational and theoretical indications that q' decreases at lower diameters. Figs 8 and 9 show the debiased distributions of observed Centaurs with $a < 60$ au in a model with $q' = 4$ for $H < 8$ and $q' = 1$ for $H > 8$ (cf. Davis, Farinella & Weidenschilling 1999; Bernstein et al. 2004). As can be seen, these figures provide an even poorer fit to the corresponding predicted distributions for Centaurs with $a < 60$ au (Figs 2 and 3).

A possible explanation for our failure to resolve the discrepancies in this way is cometary activity. This would lead to our overestimating the sizes of Centaurs (especially for the inner component of the population) compared to the asteroidal appearance assumed in our debiasing procedure. For this reason, we regard it as premature to come to a firm conclusion about the origin of Centaurs with

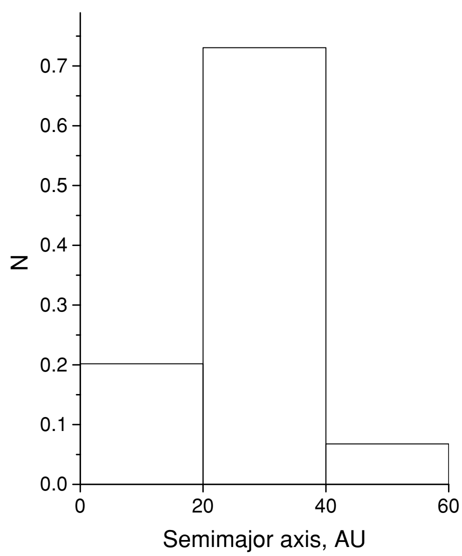

Figure 8. The debiased a distribution for observed Centaurs with $a < 60$ au assuming $q' = 4$ for $H < 8$ and $q' = 1$ for $H > 8$.

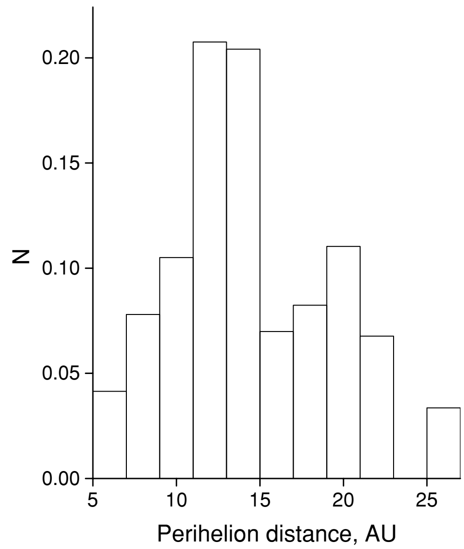

Figure 9. The debiased q distribution for observed Centaurs with $a < 60$ au assuming $q' = 4$ for $H < 8$ and $q' = 1$ for $H > 8$.

$a < 60$ au from high-eccentricity TNOs, and focus our discussion on objects with $a > 60$ au.

4 DYNAMICAL FEATURES OF CENTAURS WITH SEMIMAJOR AXES ABOVE 60 au

There are four multiple-opposition Centaurs with $a > 60$ au in the list of the Minor Planet Center, shown here in Table 1. The object (65489) had $|\beta| > 5°$ at discovery, and so was not included in the above histograms. In Table 1, s is the formal weight w of each object with respect to the total weight of all Centaurs with $a < 60$ au, obtained by the debiasing procedure described above. We have carried out new integrations of 200 clones for each of these four objects, varying a in each case within the range of uncertainties.

The integrations were performed using the same symplectic integrator (Emel'yanenko 2002; Emel'yanenko et al. 2003), including perturbations from the four outer planets and with the mass of the inner planets added to the Sun. For objects with $a > 1000$ au, we also take into account the Galaxy and stars in the way described by Emel'yanenko (1999). The integrations were continued for 4.5 Gyr, unless the object was captured to $q < 2.5$ au, evolved to a hyperbolic orbit or had a close encounter with a star. In Table 1, $p_{\rm JF}$ and $p_{\rm HT}$ are the estimated probabilities of capture to the Jupiter family and Halley-type orbits, respectively, and $L_{\rm ej}$ is the mean time of evolution for objects ejected to hyperbolic orbits or to the Oort cloud due to close encounters with stars. Here, we define the Jupiter family as corresponding to $q < 2.5$ au and Tisserand parameter with respect to Jupiter $T > 2$, and Halley-type orbits are defined as $q < 2.5$ au and $T < 2$.

Table 1. Multiple-opposition Centaurs with $a > 60$ au. 2003 FX_{128} and 1999 TD_{10} are now the numbered objects (65489) and (29981), respectively.

	a (au)	q (au)	i (°)	s	$p_{\rm JF}$	$p_{\rm HT}$	$L_{\rm ej}$ (Myr)
2000 OO_{67}	514	20.8	20.1	7.2	0.005	0.000	258
2003 FX_{128}	104	17.8	22.3	2.2	0.030	0.000	226
1999 TD_{10}	95.7	12.3	6.0	0.1	0.040	0.000	38
2002 XU_{93}	67.4	21.0	77.9	2.1	0.000	0.008	1041

Table 1 shows that the dynamical behaviour of Centaurs with $a > 60$ au is quite different from that of Centaurs with $a < 60$ au. The evolution of Centaurs with relatively small values of a has been investigated by Tiscareno & Malhotra (2003) and Horner et al. (2004a), who show that about one-third of these objects evolve to the JF population. By contrast, Table 1 shows that the probability of Centaurs with $a > 60$ au evolving to JF orbits is much smaller. Moreover, these Centaurs (objects such as 2002 XU_{93}) may produce Halley-type comets, whereas we did not find any example of a Halley-type object originating from the NNHE sample (Emel'yanenko et al. 2004).

An evident source of objects on high-eccentricity orbits with $5 < q < 28$ au and $a > 60$ au is the Oort cloud. In Table 1, $L_{\rm ej}$ can be expected to give a rough estimate of the time for the evolution from the Oort cloud to the present orbit for each object.

5 DISCUSSION

This study of the observed distribution of Centaurs (i.e. objects with $5 < q < 28$ au) has shown that there are two separate, but overlapping classes of Centaurs, differing in both numbers and dynamical features. The majority (approximately 90 per cent) have $a > 60$ au, and probably originate from the Oort cloud. Our debiased observations suggest that the intrinsic number of observed Centaurs with $a > 60$ au is approximately 0.12 times the number of objects in the NNHE region. Our results also show that the predicted distribution of Tisserand parameters and inclinations for JF objects captured from Centaurs with $a > 60$ au is consistent with observations (see Fig. 10).

There are many indications that the Oort cloud can produce a significant flux of objects with relatively small semimajor axes, for example Halley-type comets. In this case, it is well known that the predicted flux of Halley-type comets (ignoring fading) is at least a hundred times greater than the original near-parabolic flux (Emel'yanenko & Bailey 1998). Similarly, we would expect to find a

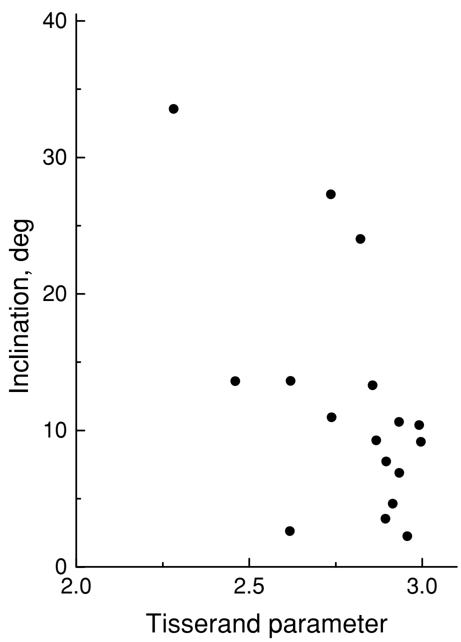

Figure 10. The distribution of Tisserand parameters and inclinations for simulated objects from the region $5 < q < 28$ au, $a > 60$ au when their perihelia first drop below 2.5 au.

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significant flux of dynamically evolved objects from the Oort cloud in the Centaur zone (e.g. Emel'yanenko 1999).

The second, minority class of Centaurs, comprising objects with $a < 60$ au, is more problematic. These are usually thought to arise as a result of evolution of so-called 'Scattered Disc' objects (i.e. objects with orbits similar to those in the NNHE region). However, the presently observed Centaur distribution is inconsistent with such a model. For example, the observed fraction of objects with relatively small a and q is too large compared with the outer component. There remains a possibility that this discrepancy could be resolved by the inclusion of physical factors that may affect the evolution or appearance of Centaurs at relatively small heliocentric distances. However, if this is not the case, the majority of Centaurs with $a <$ 60 au must also have another source.

Nevertheless, assuming that Centaurs with $a < 60$ au come mainly from the NNHE region (and with out-gassing or other physical factors explaining the discrepancy), our computations show that their number should be approximately 0.005 times the number of NNHE objects (see the last paragraph of Section 2). The observed number of objects in the outer portion of this class ($40 < a < 60$ au) is not inconsistent with this picture. If Centaurs with $a < 60$ au originate from the NNHE region, therefore, the steady-state number of such Centaurs should be $0.005/0.12 = 0.04$ times the number of Centaurs with $a > 60$ au.

In this case, the long-standing problem of the origin of JF comets re-emerges. The mean transfer probability (using the weights in Table 1) for Centaurs with $a > 60$ au to evolve to JF comets is 0.009. This is much smaller than the value ($\sim 1/3$) found for the evolution of observed Centaurs to JF comets (Tiscareno & Malhotra 2003; Horner et al. 2004a). However, assuming that Centaurs with $a < 60$ au come mainly from the NNHE region, we have shown that there are many more Centaurs with $a > 60$ au than Centaurs with $a < 60$ au, by a factor of approximately 25 to 1. Therefore, although the transfer probability for Centaurs with $a > 60$ au to evolve to the JF is much less than that for Centaurs with $a < 60$ au, the relative numbers of Centaurs in these two JF source regions leads to each region producing a similar number of JF comets, the ratio being approximately 25×0.009 to 1/3, i.e. 0.7 to 1. This suggests that approximately 40 per cent of JF comets originate from Centaurs with $a > 60$ au, and so come from the Oort cloud. Moreover, observational selection effects tend to favour the discovery of objects with relatively small q and a, causing such orbits to be over-represented in the the various integration studies. The mean transfer probability for Centaurs with $a < 60$ au to JF orbits should therefore probably be reduced below 1/3. In this case, the relative number of JF comets originating in the Oort cloud would be larger.

Thus, we have shown that there are at least two sources of observed Centaurs, most importantly a dominant Oort cloud source with $a \gtrsim 60$ au. Centaurs with smaller semimajor axes ($a \lesssim$ 60 au) may originate from the observed NNHE region, but they may also come from the Oort cloud. It is difficult to determine exactly the dynamical characteristics of Centaurs originating from the Oort cloud because of our incomplete knowledge of the structure of the Oort cloud and the relatively small number of known Centaurs with $a \gtrsim 60$ au. Nevertheless, our preliminary estimates suggest that the Oort cloud and the NNHE region produce roughly equal numbers of Centaurs with $a < 60$ au (as with their relative production of JF comets). Seen from this perspective it is remarkable that photometric investigations now clearly demonstrate the existence of two distinct populations of Centaurs with different colours (Peixinho et al. 2003, 2004).

6 CONCLUSIONS

Our principal conclusions are as follows.

(i) There are two dynamically distinct classes of Centaurs, a dominant group with $a \gtrsim 60$ au and a minority group with $a \lesssim 60$ au. The dominant group is an order of magnitude larger than that with $a < 60$ au, and its orbital characteristics show that it cannot originate from the NNHE region. We suggest that the most likely source for this dominant class of Centaurs is the Oort cloud.

(ii) The NNHE region produces Centaurs mostly having $a <$ 60 au. Taken at face value, their predicted orbital distribution is inconsistent with observations, although the discrepancy might be explained by the effects of physical factors such as out-gassing, splitting or changing albedo.

(iii) The orbits of dynamically evolved objects from the NNHE region and of dynamically evolved Oort cloud comets with q in the planetary region overlap in the range $a < 60$ au where they become Centaurs and short-period comets. Although the number of known Centaurs is insufficient to determine exactly the relative contribution of the two sources, according to the present observational data they produce roughly similar numbers of Centaurs with $a < 60$ au, and also roughly similar numbers of JF comets.

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