ABSTRACT
A symplectic integrator is used to study the evolution of high-eccentricity trans-Neptunian objects (TNOs) over the age of the Solar system. For 26 objects, a few cloned orbits were integrated. We demonstrate the existence of several known bodies that are in relatively stable orbits located far from Neptune for the age of the Solar system. Thus, we provide an indication of the structure of the protoplanetary disc immediately after the period of planet formation. The orbits of these bodies cannot be explained by a model in which a near-Neptune disc of planetesimals is gravitationally scattered by Neptune. In this paper, therefore, we demonstrate the existence of a new, and populous, class of 'outer' TNOs which have substantially different dynamical characteristics from those of scattered disc objects.

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

1 INTRODUCTION
Following the discovery in 1992 of the first trans-Neptunian object (TNO) other than Pluto, more than 600 objects with diameters in the approximate range of 100–1000 km have so far been identified with orbits carrying them beyond the conventional 'planetary' system. The spatial distribution of these bodies, which are widely believed to be cometary in composition (although classified as minor planets on account of their asteroidal or star-like appearance), comprises a flattened disc or belt-like structure, extending hundreds of astronomical units (au) or more from the Sun.

The core of the belt is referred to as the Kuiper belt or the Edgeworth–Kuiper belt (EKB). Seen in projection, the disc is concentrated within a rather narrow range of ecliptic latitude (half-width $\beta_{1/2} \simeq 3°$–$5°$), but closer analysis of the inclination distribution provides evidence for a surprisingly high level of dynamical excitation, approximating a Gaussian distribution with dispersion $\sigma_i \simeq 15°$ (Brown 2001; Trujillo, Jewitt & Luu 2001). This suggests that the orbits of the Edgeworth–Kuiper belt objects (EKOs) have been significantly disturbed since they were first formed on the outskirts of the protoplanetary disc. It is now accepted that the EKB, like the main asteroid belt, is presently in a collisionally dominated rather than accretional regime (e.g. Stern & Colwell 1997).

A further important feature of the distribution of EKO orbits is that there is growing evidence for an outer boundary at a heliocentric distance of the order of 50 au (Jewitt, Luu & Trujillo 1998; Allen, Bernstein & Malhotra 2001; Trujillo et al. 2001), close to the semi-major axis $a$ corresponding to the 1:2 mean-motion resonance with Neptune (i.e. $\simeq 48$ au), although many TNOs have orbits that extend significantly beyond this distance. It is not yet known whether the TNO distribution at greater distances is spatially limited or joins (smoothly or otherwise) on to a more extended, flared disc and inner core of the Oort cloud, as might be expected for example by the planetesimal theory of planet formation (e.g. Fernández 1985; cf. Bailey, Clube & Napier 1990).

The origin and explanation of the orbital distribution of these large, newly discovered objects are not fully understood, nor is it known what role (if any) they played in planet formation, and what role they continue to play in questions such as the origin of short-period comets and the evolution of the Oort cloud. The fact that TNOs are located far from the Sun in an extremely cold environment suggests that, apart from possibly significant collisional evolution (Stern 1995; Farinella & Davis 1996), they should be primitive, ‘primordial’ bodies, containing important clues to the structure and evolution of the protosolar and protoplanetary nebula more than 4 Gyr ago. In particular, earlier work by Duncan, Levison & Budd (1995) has shown that the majority of low-eccentricity EKOs with initial semimajor axes greater than 42 au have orbits that are stable for at least the age of the Solar system, the zone of stability widening with increasing perihelion distance. The fact that many of the currently known objects have orbits with perihelion distances greater than 40 au thus suggests that their dynamical evolution under the influence of known planetary perturbations should be extremely slow, and that their orbital distribution will provide crucial information about conditions on the outskirts of the protoplanetary disc at or soon after the time of planet formation.
1.1 Dynamical classification

1.1.1 Trans-Neptunian objects

The known TNOs can be divided on the basis of their orbital elements and dynamical characteristics into five main groups, which we label for convenience: O, P, Q, R and S. Groups O and S, which are essentially objects with \( a \gtrsim 50 \) au and which are the main subject of this paper, contain at least as many objects as the ‘classical’ EKB comprising the remaining groups P, Q and R. Lying near the edge of the main or ‘classical’ EKB, these distant objects mainly have rather eccentric orbits, perihelion distances beyond Neptune, large \( a \), and aphelion distances ranging up to 400 au or more.

This population was first recognized with the discovery of 1996 TL66 (Luu et al. 1997), which has eccentricity \( e = 0.59 \), semimajor axis \( a = 85 \) au, perihelion distance \( q = 35.0 \) au and aphelion distance \( Q = 135 \) au. This combination of orbital properties placed the object initially in a class of its own, being quite distinct from any other EKO then known, and immediately raised the prospect of a new, populous class of TNO.

1996 TL66 and subsequently discovered objects with large \( a \) are widely believed to have originated through dynamical evolution or scattering from initial orbits located close to Neptune, and have hence been called ‘scattered disc objects’ (‘Class S’) (Luu et al. 1997). However, rather than being ‘scattered’ by distant encounters with Neptune (cf. Duncan & Levison 1997), many of these bodies – as we show below – have very long dynamical lifetimes, and are dynamically stable under the influence of known planetary perturbations for time-scales comparable to or much longer than the age of the Solar system. It is therefore appropriate to introduce an additional, dynamically distinct class of outer Solar system objects, which we call Class O.

However, unlike the classical EKOs, the high eccentricity and moderately high inclination of these outer objects is at odds with the standard planetesimal picture for the origin of comets in a dynamically cold disc. Instead they suggest a possible dynamical link with the inner core of the Oort cloud and a connection with alternative theories of comet formation, such as those explored by Biermann & Michel (1978) and Hills (1982). The existence of these objects thus plays a fundamental role in constraining the properties and evolution of the protoplanetary disc at about the time of the formation of the outer planets.

The remaining three dynamical classes, which we call Classes P, Q and R, are associated with the ‘classical’ EKB and extend to approximately 50 au. Plutinos (Class P) have orbits similar to that of Pluto, lying in the 2:3 mean-motion resonance with Neptune, and extend to periods of revolution close to 250 yr. ‘Cubewanos’ (Class Q) are named after the prototype (15760) 1992 QB₁, the first EKO to be found. They have orbits of moderately low eccentricity and inclination, perihelion distances beyond the range of Neptune’s immediate influence (i.e. \( q \gtrsim 33 \) au), and semimajor axes below about 48 au, the limit corresponding to the 1:2 mean-motion resonance with Neptune.

The third group, ‘Resonant’ objects (Class R), are also in low-order mean-motion resonances with Neptune (other than 2:3), for example 1:2, 3:5, 3:4 and 4:5, having orbital periods around 330, 275, 220 and 206 yr, respectively. We consider these as a separate class from the Plutinos largely because their total number appears to be far smaller than expected on the basis of the relative strength of the respective resonances.

As far as numbers in each class are concerned (Trujillo et al. 2001), Classes O, S and Q are similar, while Classes P and R contain roughly an order of magnitude fewer objects. Discovery biases favour Plutinos in the observed data set, while other resonant objects (Class R) together comprise only a few per cent of observed objects. As far as the origin of TNOs is concerned, attention must therefore focus on Classes O and Q – Class S merely comprising transition objects en route from one or another source to the dynamical end state of capture to a short-period orbit or ejection.

1.1.2 Centaurs

A sixth class of distant Solar system object, namely Centaurs, has also been identified. These are also large bodies – comets or asteroids – but currently move on dynamically short-lived, chaotic orbits under the dominant influence of one or more of the four major planets. The first to be discovered, namely (2060) Chiron, was found in 1977, but it was another 15 years before the second such object, (5145) Pholus, was identified. The Centaurs are usually considered to be evolving inwards from more distant source reservoirs (the EKB or possibly the Oort cloud), en route to becoming Jupiter-family comets, although some at least must be at stages of their evolution following an episode of small perihelion distance (Hahn & Bailey 1990).

There are now some 50 Centaurs known, with sizes presumably similar to the EKB and Oort cloud size distributions ranging up to more than 200 km. The aphelia of their orbits, like those of Classes O and S, sometimes reach far beyond Neptune, up to 100 au or more. However, unlike either of these classes the Centaurs have exceptionally short dynamical lifetimes (10⁵–10⁷ yr).

There is not yet a universal definition of ‘Centaur’ and sometimes orbits with a larger than, say, Neptune are excluded. Here, however, we consider that their important characteristic is to cross or closely approach the region of the giant planets, even if \( Q \) is large. The Minor Planet Center (MPC) currently provides a common reference list (‘Centaurs and Scattered-Disc Objects’) for TNOs in high-e orbits (i.e. our Classes O and S) and Centaurs. Here we note the link between Centaurs and Class S, but emphasize instead the presence of a dynamically stable outer reservoir, Class O.

We note that Centaurs are almost invariably under the dynamical control of one or another outer planet (Jupiter, Saturn, Uranus or Neptune), and that their orbits can be classified in terms of that planet and whether their aphelion distance reaches another planet or extends to a more distant region. For example, in this classification scheme (Horner et al., in preparation) ‘SU’ would denote an orbit with perihelion near Saturn and aphelion near Uranus, such as (2060) Chiron; and ‘UE’ would denote a Centaur with a perihelion distance near Uranus and aphelion in the EKB, e.g. (33128) 1998 BU₄₈.

Some Centaurs, whether under the principal control of Neptune or another planet, can be temporarily scattered on to Neptune-crossing orbits, as seen during long-term numerical investigations of Centaur orbits (e.g. Hahn & Bailey 1990). Further examples of Centaurs in Neptune-crossing or Neptune-approaching orbits, with aphelion in the EKB or beyond, include the massive object 1995 SN₃₅ (classified ‘SE’), with diameter \( d \approx 430 \) km (assuming a visual geometric albedo \( p_V = 0.04 \), and the even larger object (26375) 1999 DE₄₈ (with \( d \approx 800 \) km).

In summary, the known outer solar system objects can be conveniently divided into six classes: Centaurs (objects on planet-crossing orbits under the dynamical influence of one or more of the major planets); and Classes O, P, Q, R and S (objects in or beyond the ‘classical’ EKB, being respectively, high-eccentricity, dynamically long-lived ‘outer’ objects; plutinos; cubewanos; resonant objects other than plutinos; and scattered disc objects). In this paper, we...
focus mainly on the distinction between Classes O and S, and note that the dynamical lifetimes of objects in the latter class are usually much shorter than the age of the Solar system. Hence attention is drawn to Class O as the ultimate reservoir.

1.2 Interrelationships
The idea (Edgeworth 1943; Kuiper 1951; Whipple 1964; Whipple 1972) that the EKB could be a principal source of short-period comets was taken up by Fernández (1980), and subsequently developed by Levison & Duncan (1997), who have shown that there are many regions of weak instability within the EKB (orbits primarily of Class Q) which could provide a sufficient flux of objects on Neptune-encountering orbits to explain the observed number and inclination distribution of Jupiter-family comets. Indeed, many high-eccentricity TNOs are under the gravitational control of Neptune, and are closely connected in principle to the observed Centaur populations, because there is a direct route, through planetary perturbations, linking eccentric Neptune-crossing orbits to objects with shorter orbital periods and smaller perihelia. Such objects may perturbations, linking eccentric Neptune-crossing orbits to objects with shorter orbital periods and smaller perihelia. Such objects may ultimately become Uranus-crossing, Saturn-crossing and Jupiter-crossing (Kazimirchak-Polonskaya 1972), finally appearing as bona fide members of the Jupiter-family short-period comet system. On the other hand, as suggested by Duncan & Levison (1997), the scattered population (Class S) could also produce Jupiter-family comets, and might itself be explained as a by-product of the ejection of primordial Neptune-zone planetesimals on to high-eccentricity orbits by the proto-Neptune or by growing planetary embryos in Neptune’s accretion zone.

However, the recent discovery of many objects in high-eccentricity non-Neptune interacting orbits puts these discussions in a new light. Because many high-eccentricity TNOs with \( a \gtrsim 50 \) au have perihelion distances located far from Neptune’s orbit (e.g. 2000 CR\(_{105}\), with \( q = 44.2 \) au and \( a = 230 \) au), the small chaotic diffusion of the orbital parameters at large \( q \) may not be enough for the object ever to encounter Neptune. Therefore, such objects cannot be ‘scattered’ by Neptune from a near-Neptune disc, and must have another origin.

In this paper, we investigate the dynamical evolution of a sample of well-observed TNOs with \( a \gtrsim 50 \) au. This sample allows us to prove the existence of a new class of TNOs (Class O), with high-eccentricity orbits and dynamical features that are quite different from either Centaurs or scattered disc objects. These ‘outer’ TNOs generally have long-lived, nearly stable orbits with lifetimes – like those of planets and most main-belt asteroids – measured in billions of years, i.e. at least as long as the age of the Solar system. They therefore provide crucial clues to the structure and early evolution of the primordial protoplanetary disc.

2 INTEGRATIONS OF KNOWN OBJECTS AND THEIR CLONES

2.1 Method
We have chosen 26 TNOs (Table 1) with heliocentric, \( a > 49.9 \) au and \( q > 30.9 \) au, elements being converted to barycentric before integrating (Fig. 1). We looked up the best-fitting orbit using data published by the MPC. For every object, this and six other cloned orbits were integrated.

The best-fitting orbit and its clones had the same initial orbital elements except for the semimajor axis, which can be uncertain and is the element for which the orbital evolution is most sensitive. The initial \( a \) of clones was taken to lie in the interval \( (a - \Delta a, a + \Delta a) \) centred on the best-fitting orbit, successive clones differing by \( \Delta a/3 \) and

Table 1. Heliocentric orbital elements at epoch 2001 Oct. 18.0, including \( \Delta a \) values used to generate clones (Section 2.1).

<table>
<thead>
<tr>
<th>( a ) (au)</th>
<th>( \Delta a ) (au)</th>
<th>( e )</th>
<th>( q ) (au)</th>
<th>( i ) (deg)</th>
<th>( \Omega ) (deg)</th>
<th>( \omega ) (deg)</th>
<th>( M ) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 RZ(_{215})</td>
<td>101.0</td>
<td>2.98</td>
<td>0.69</td>
<td>31.0</td>
<td>25.5</td>
<td>341.6</td>
<td>336.5</td>
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<tr>
<td>1998 WA(_{31})</td>
<td>55.4</td>
<td>0.03</td>
<td>0.43</td>
<td>31.7</td>
<td>9.4</td>
<td>20.7</td>
<td>310.5</td>
</tr>
<tr>
<td>(26375)</td>
<td>1999 DE(_9)</td>
<td>55.9</td>
<td>0.01</td>
<td>0.42</td>
<td>32.2</td>
<td>7.6</td>
<td>322.9</td>
</tr>
<tr>
<td>(38084)</td>
<td>1999 HB(_{12})</td>
<td>55.4</td>
<td>0.15</td>
<td>0.41</td>
<td>32.6</td>
<td>13.2</td>
<td>166.4</td>
</tr>
<tr>
<td>2000 PE(_8)</td>
<td>55.4</td>
<td>0.60</td>
<td>0.40</td>
<td>33.0</td>
<td>5.9</td>
<td>3.9</td>
<td>142.9</td>
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<tr>
<td>1999 CY(_{118})</td>
<td>91.1</td>
<td>0.52</td>
<td>0.62</td>
<td>34.6</td>
<td>25.6</td>
<td>163.1</td>
<td>15.3</td>
</tr>
<tr>
<td>1999 RZ(_{125})</td>
<td>59.4</td>
<td>3.49</td>
<td>0.42</td>
<td>34.7</td>
<td>19.7</td>
<td>315.0</td>
<td>43.8</td>
</tr>
<tr>
<td>2000 CQ(_{105})</td>
<td>57.1</td>
<td>0.72</td>
<td>0.39</td>
<td>34.9</td>
<td>19.6</td>
<td>317.6</td>
<td>102.6</td>
</tr>
<tr>
<td>1996 TL(_{66})</td>
<td>84.9</td>
<td>0.10</td>
<td>0.59</td>
<td>35.0</td>
<td>23.9</td>
<td>217.8</td>
<td>184.8</td>
</tr>
<tr>
<td>(15874)</td>
<td>1999 CG(_{119})</td>
<td>49.9</td>
<td>0.12</td>
<td>0.29</td>
<td>35.2</td>
<td>16.6</td>
<td>304.3</td>
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<tr>
<td>2000 PE(_{30})</td>
<td>53.4</td>
<td>2.68</td>
<td>0.32</td>
<td>36.1</td>
<td>18.4</td>
<td>127.4</td>
<td>152.2</td>
</tr>
<tr>
<td>2000 YC(_2)</td>
<td>58.5</td>
<td>3.37</td>
<td>0.38</td>
<td>36.4</td>
<td>19.8</td>
<td>227.6</td>
<td>149.0</td>
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<tr>
<td>1998 XY(_{95})</td>
<td>65.1</td>
<td>0.22</td>
<td>0.43</td>
<td>37.4</td>
<td>6.7</td>
<td>47.3</td>
<td>88.9</td>
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<td>1999 CV(_{118})</td>
<td>53.2</td>
<td>2.64</td>
<td>0.29</td>
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<td>0.21</td>
<td>0.67</td>
<td>37.7</td>
<td>27.7</td>
<td>345.2</td>
<td>235.9</td>
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<td>119.3</td>
<td>4.52</td>
<td>0.68</td>
<td>37.9</td>
<td>25.9</td>
<td>210.3</td>
<td>141.1</td>
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<td>2000 PF(_{30})</td>
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<td>0.33</td>
<td>0.50</td>
<td>38.0</td>
<td>6.3</td>
<td>293.7</td>
<td>337.6</td>
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<td>(26181)</td>
<td>1996 GQ(_{21})</td>
<td>92.8</td>
<td>0.01</td>
<td>0.59</td>
<td>38.2</td>
<td>13.4</td>
<td>194.2</td>
</tr>
<tr>
<td>1999 CF(_{119})</td>
<td>90.2</td>
<td>0.51</td>
<td>0.57</td>
<td>38.7</td>
<td>19.7</td>
<td>303.4</td>
<td>199.9</td>
</tr>
<tr>
<td>1999 CC(_{158})</td>
<td>54.4</td>
<td>0.14</td>
<td>0.28</td>
<td>39.1</td>
<td>18.7</td>
<td>337.0</td>
<td>102.0</td>
</tr>
<tr>
<td>1999 HW(_{11})</td>
<td>52.4</td>
<td>0.13</td>
<td>0.25</td>
<td>39.2</td>
<td>17.2</td>
<td>198.4</td>
<td>324.1</td>
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<tr>
<td>2000 OM(_{67})</td>
<td>97.8</td>
<td>0.62</td>
<td>0.60</td>
<td>39.3</td>
<td>23.4</td>
<td>327.1</td>
<td>349.3</td>
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<td>2000 PH(_{30})</td>
<td>71.1</td>
<td>5.48</td>
<td>0.44</td>
<td>39.6</td>
<td>8.1</td>
<td>127.2</td>
<td>238.7</td>
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<td>1995 TL(_{8})</td>
<td>52.7</td>
<td>0.13</td>
<td>0.24</td>
<td>40.2</td>
<td>0.2</td>
<td>261.6</td>
<td>84.8</td>
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<td>2000 YW(_{134})</td>
<td>58.2</td>
<td>3.32</td>
<td>0.29</td>
<td>41.3</td>
<td>19.8</td>
<td>127.0</td>
<td>318.4</td>
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<tr>
<td>2000 CR(_{105})</td>
<td>229.7</td>
<td>1.19</td>
<td>0.81</td>
<td>44.2</td>
<td>22.7</td>
<td>128.3</td>
<td>317.0</td>
</tr>
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</table>
with Δa calculated by the following procedure, depending on the orbital uncertainty.

The MPC defines an uncertainty parameter U, an integer in the range 0 to 9, that quantifies the in-orbit longitude run-off expected to occur over time. The orbital run-off results from the uncertainty in a and in the perihelion passage time T. Taking the value of U calculated by the MPC, and assuming the uncertainty to be wholly due to a rather than T, yielded the uncertainty Δa that we adopted to generate the clones. Only orbits with U ≤ 6 were included; otherwise the uncertainty can be large enough that the calculated value of a is somewhat meaningless. This led to a total of 26 objects, all multiple opposition. We confirmed that this selection of 26 objects was consistent with the MPC data set that was current on 2002 January 30.

The results were produced using the symplectic integrator of Emel’yanenko (2002). This explicit second-order integrator can handle both high-eccentricity orbits and close encounters with planets. The symplectic integration is performed in the barycentric coordinate system with a constant step over the variable t, which is connected with time r by the expression \(dr = (R + B/r) dt\), where R is the value of the perturbing function, B is a small constant chosen so as to ensure sufficient precision of the integration over long time-scales, and r is the distance from the barycentre. In the absence of close encounters, \(R \ll B/r\), and the time-step is practically proportional to r. The step-size over the variable t for the majority of the particles was chosen so that it corresponded to 0.5 yr at \(r = 100\) au unless a smaller value was chosen (e.g. for objects more likely to evolve to large a and perihelion distances significantly beyond Neptune) so as to ensure sufficient precision in the computed results. We included the perturbations from the four outer planets, with the mass of the inner planets being added to that of the Sun, and planetary coordinates were calculated on the basis of the secular theory of perturbations (Brouwer & van Woerkom 1950; Sharaf & Budnikova 1967). In most cases, the integration was continued for 4.5 Gyr, unless the orbit evolved to \(q < 25\) au or \(a > 1000\) au, the former indicating an unstable Centaur-like ‘end state’ and the latter an orbit likely to be influenced by unmodelled external perturbations (e.g. due to stars or the Galactic tide).

### 2.2 Results

Our calculations show a range of different dynamical behaviours for the investigated objects. For example, our results are consistent with the conclusion of Gladman et al. (2002) that 2000 CR105 demonstrates a chaotic motion despite its large perihelion distance; but the rate of diffusion in the perihelion distance is too slow for it to approach the near-Neptune region during the age of the Solar system. We have also found evidence that other TNOs have large-q orbits for 4.5 Gyr, namely: (26181); 1995 TL4; 1999 CC158; 2000 PF3; 2000 PH30; 2000 YW134; 2000 OM57; and 1999 CV118. The changes of a and q for the best-fitting orbits and their clones are presented in Fig. 2. Except for 1999 CV118 and 2000 OM57, all these objects have \(q > 35\) au for the entire period of the integrations.

Formally, no clone of 1999 CV118 and 2000 OM57 has any close encounters with Neptune. But one clone of 1999 CV118 reaches a perihelion distance of 31.4 au, and three clones of 2000 OM57 move on orbits scarcely different, with \(\sim 33\)–34 au and very large semimajor axes (two reached \(a > 1000\) au at which point they were removed from the integration). The objects 1999 CF119, 1999 RD214, 1998 XY35 (cf. Collander-Brown et al. 2001) and 1999 HW11 have similar dynamical behaviour to 1999 CV118, in that some of their clones reach the near-Neptune region. However, the uncertainty of their orbits does not allow us to answer reliably the question whether these objects could have been scattered by Neptune.

The majority of clones for the other objects (with initial \(q < 37\) au) show unstable behaviour, as do most of the clones of 1999 CZ118 (whose initial q is just a little higher). Although some of these, i.e. (26375), (38084), 1998 WA31, 2000 FE5, initially move close to the 2:5 resonance with Neptune, the range in q for the clones of these objects is sufficiently large that many reach the near-Neptune region within the age of the Solar system.

### 3 IMPLICATIONS

Our investigation has shown that it is unlikely that many observed high-eccentricity TNOs can reach the vicinity of Neptune within...
the age of the Solar system. These results require the concept of the scattered disc as the main source of such objects to be reassessed.

To examine this further, we have calculated where the majority of bodies should be located if they are scattered by Neptune. For this purpose, we studied a simple model of bodies originating from the near-Neptune region. We integrated 1000 test particle trajectories for 4.5 Gyr, taking into account the perturbations from the four outer planets. Initial perihelion distances and semi-major axes were uniformly distributed in the intervals (30, 32) au and (34, 50) au, respectively, i.e. corresponding to initial Neptune-approaching or Centaur (Section 1.1.2) orbits, similar to the initial conditions used by Levison & Duncan (1997) in their investigation of objects evolving out of the EKB as a result of encounters.
with Neptune. Initial inclinations were distributed between 0 and 40 degrees according to the sine law. Again, we stopped our integrations if \( a > 1000 \) au (as with Levison & Duncan 1997) or \( q < 25 \) au.

Fig. 3 represents the steady-state distribution of \( q \) and \( a \) for these test particles, generated by recording elements every 1000 revolutions and at the end counting orbits in equal-sized \((a, q)\) bins. Comparing this plot with Fig. 1 shows that the majority of observed TNOs with \( a > 50 \) au are located at much higher \( q \) than these test particles at any stage of the latter’s evolution. Thus, despite uncertainties in the initial distribution, and the limited number (26) of objects on which these conclusions are based, it is clear that the majority of TNOs with large semimajor axes cannot originate from a scattered disc population. Fig. 3 shows that, if the model of the scattered disc as a sole source of objects in high-eccentricity orbits were valid, the number of observed scattered objects with \( q < 38 \) au

\[ \text{Figure 2 – continued} \]
should be very much greater than the number of observed objects with larger $q$, contrary to Fig. 1.

4 CONCLUSIONS

Our work shows that there exists a new class of TNOs, which we call Class O or ‘outer’ TNOs. These cannot originate from Centaurs or Class S objects scattered by Neptune, because their dynamical lifetime in non-Neptune approaching orbits exceeds the age of the Solar system. According to present observational data, these outer TNOs are also well separated from the ‘classical’ EKB. If we consider the region $q > 38$ au, where changes in the orbit are small even over long time-scales, there is currently a gap of about 5 au between the semimajor axes of ‘classical’ EKOs and O-types. The gap is centred around $a \sim 50$ au.

While early investigations of the EKB have focused on showing how small, long-term perturbations acting over some Gyr can gradually destabilize the orbits of outer Solar system bodies so that
they can be regarded as a source region for observed Centaurs and Jupiter-family comets, we have shown that the outer Class O is in fact characterized by extremely long dynamical lifetimes under the influence of known planetary perturbations.

This highlights the importance of understanding the origin of these outer objects. Unless they are affected by hitherto unidentified perturbations – see Gladman et al. (2001) for a review – their present distribution provides 'fossil' evidence of conditions in the protoplanetary disc immediately following the period of planet formation. How the objects in this population were initially formed and placed on their present orbits thus becomes a key question for understanding the early history and evolution of the Solar system.

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Figure 3. Steady-state distribution of test particles scattered by Neptune. Initially q and a were uniform in (30, 32) and (34, 50) au. Particles were allowed to evolve over 4.5 Gyr.
A new class of trans-Neptunian objects


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