A new dynamical class of object in the outer Solar System

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Some three dozen objects have now been discovered[1–5] beyond the orbit of Neptune and classified as members of the Kuiper belt—a remnant population of icy planetesimals that failed to be incorporated into planets. At still greater distances is believed to lie the Oort cloud—a massive population of cometary objects distributed approximately in a sphere of characteristic dimension 50,000 AU (ref. 6). Here we report the discovery of an object, 1996TL$_{66}$, that appears to be representative of a population of scattered bodies located between the Kuiper belt and the Oort cloud. 1996TL$_{66}$ has an orbital semimajor axis of 84 AU, and is in an extremely eccentric and highly inclined orbit ($e = 0.58$, $i = 24°$). With a red magnitude ~20.9, it is the brightest trans-neptunian object yet found since Pluto and Charon. Its discovery suggests that the Kuiper belt extends substantially beyond the 30–50 AU region sampled by previous surveys, and may contain much more mass than previously suspected.

The object 1996TL$_{66}$ was found in the course of a large-area, medium-depth survey of the outer Solar System. Most of the Kuiper-belt objects (KBOs) found to date are near the brightness limit of ground-based telescopes (red magnitude $m_R > 22$), severely restricting opportunities for physical study. One of the goals of the large-area survey is to remedy this situation by searching for larger (brighter) trans-neptunian objects. This search makes use of a unique large-format charge-coupled device (CCD) mounted on the University of Hawaii 2.2-m telescope. The 8K CCD is an array of eight CCDs, each 2,048 × 4,096 pixels. The detector was used in 3 × 3 binning mode, resulting in a scale 0.41 arcsec per binned pixel and a total field of view of 18.4 × 18.4 arcmin, or 0.09 square degrees. Moving objects are detected in near-real time using a computer algorithm developed specifically for this purpose[7]. Sample images of 1996TL$_{66}$ are shown in Fig. 1.

On attempting orbital representations from the initial data in October 1996, it was apparent that the orbit of 1996TL$_{66}$ was quite highly inclined, and it seemed plausible that the object was of the 'Plutino' type[2]. Plutinos resemble Pluto in that they are librators in the 2 : 3 mean-motion resonance with Neptune (semimajor axis $a \approx 39$ AU), which protects them from close encounters with the planet[8]. The Plutinos make up 30–40% of the known Kuiper-belt population, the other members of which are mostly confined to low-eccentricity, low-inclination orbits with $42 \leqslant a \leqslant 46$ AU (refs 8,9). Follow-up observations in December 1996 revealed discrepancies between the recorded positions and the Plutino-type predictions that were too large to be absorbed into a 2 : 3-resonant orbit solution. It was clear that the object had to be close to the perihelion of a much more eccentric orbit[10]. The orbital elements of the best-fit orbit[11] are listed in Table 1, along with their estimated uncertainty ranges. Evidently, 1996TL$_{66}$ exhibits a new type of trans-neptunian dynamics. The distinction between 1996TL$_{66}$ and known KBOs is clear in Fig. 2. Previously discovered KBOs have orbits clustered inside ~50 AU. In contrast, the large, eccentric orbit of 1996TL$_{66}$ carries it to more than 130 AU at aphelion, and to ~35 AU at perihelion. 1996TL$_{66}$ provides the first direct evidence that the trans-neptunian population extends much further than the 30–50 AU region sampled by our previous surveys.

1996TL$_{66}$ was found after examining only 25 square degrees. The discovery of this object in such a small fraction of the sky suggests that, unless we are improbably lucky, it is merely the first detected of a larger population of similar bodies. If objects in the TL$_{66}$-class are members of a flat belt with inclinations i up to 30° (as was found for the Kuiper belt inside 50 AU; ref. 5), they would occupy a projected area of ~2×10^4 square degrees. The discovery statistics then imply that ~800 objects of this type would be detected if we extended our 8K CCD survey to the entire ecliptic band. With an assumed red geometric albedo of 4%, and heliocentric and geocentric distances of 35.2 and 34.2 AU, respectively, we estimate that 1996TL$_{66}$ has a diameter of 490 km. With bulk density 1,000 kg m^{-3}, its mass is 6×10^{19} kg ($10^{-5} M_{\rm Earth}$; $1 M_{\rm Earth} = 1$ Earth mass). The combined mass of 800 such objects is 5×10^{22} kg ($8 \times 10^{-3} M_{\rm Earth}$). This mass can be scaled to other adopted albedos, p, by the ratio $(0.04/p)^{3/2}$.

There is good reason to believe that this represents an extreme lower limit to the population of similar bodies, as a result of the effects of observational selection[2,5]. Ours is a flux-limited survey, which preferentially samples the brightest (that is, the largest and closest) objects, and those with low-inclination orbits. For example,

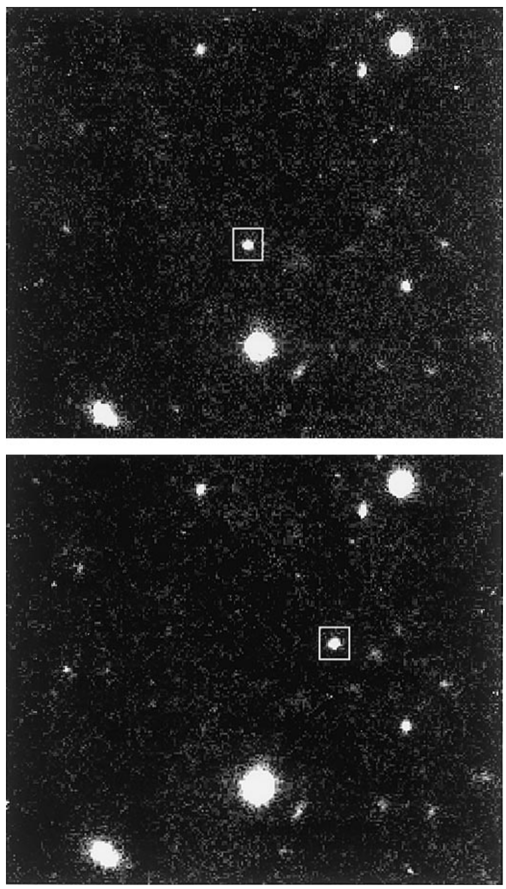

Figure 1 Object 1996TL$_{66}$ imaged on UT 1996 October 15 at 07:14 (top panel) and 12:41 (bottom panel). The field shown has north to the bottom, east to the left. Note the relative motion westward against the fixed stars. The field of view is 1.6 × 1.4 arcmin, representing 0.7% of the total area imaged by the 8K CCD mosaic. The integration time was 600 s through a broadband (5,000–7,000 Å) filter.

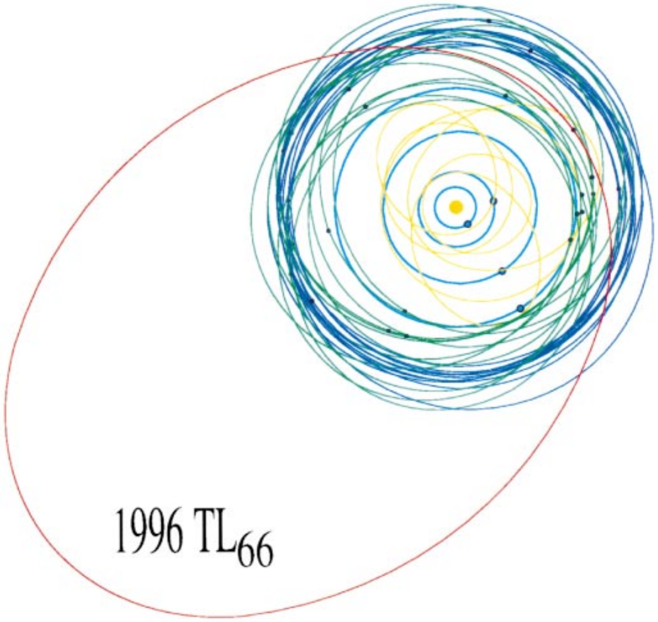

Figure 2 Planar view of the outer Solar System. The four light-blue, nearly concentric orbits are those of the giant planets. The dense band of orbits refers to the best observed Kuiper-belt objects (including Pluto), while the six yellow inner orbits refer to the Centaurs. The large, eccentric orbit of 1996TL$_{66}$ extends far beyond the previously known Kuiper belt.

1996TL$_{66}$ itself would only be bright enough to be detected in the present survey during the ~12% of its orbital period centred on perihelion. Very roughly, this suggests that the true population must be ~8 times larger than the observable population, that is ~6,400 objects (0.07 M_{Earth}). Monte Carlo simulations of a set of TL$_{66}$-like bodies are consistent with this crude estimate.

The total mass of an inverse-cube size distribution is $M = (8/3)\pi\rho N r_{\min}^2 (r_{\max} - r_{\min})$, where $\rho = 1{,}000\,\text{kg m}^{-3}$ is the bulk density of the objects, and N is the total number of objects in the radius range $r_{\min} \leqslant r \leqslant r_{\max}$. If we take $r_{\min}$ to be the radius of 1996TL$_{66}$ and $r_{\max} = 1{,}100$ km (that is, Pluto-sized), this relation yields a total mass of 2.8×10^{24} kg (0.5 M_{Earth}) contained in TL$_{66}$-like objects or larger between ~40 and 200 AU. The mass estimated here is larger than the (0.06–0.25) M_{Earth} estimated mass of the inner Kuiper belt[5], but nevertheless consistent with the dynamical upper limit[10] of ~1 M_{Earth} inside 100 AU. The inverse-cube size distribution further predicts ~4×10^8 objects (comets) with radius $1\,\text{km} \leqslant r \leqslant 245\,\text{km}$, in the same volume. These estimates are obviously crude, given the discovery statistics of 1 and the uncertainties in the projected area occupied by the TL$_{66}$ population; however, there is little doubt that the region out to at least to a few hundred AUs is substantially populated.

What is the likely origin of this new class of objects? In his discussion of the Uranus–Neptune region as the likely birthplace of icy conglomerates[13] in the Oort cloud[6], Kuiper[14] envisaged that the outer planets gravitationally ejected protocomets from that region onto large eccentric trajectories. This basic idea has been refined by others[15–17]. These works suggest that the trans-neptunian population should contain two groups of planetesimals: those on primordial near-circular orbits (which we identify with the classical Kuiper belt, albeit modified by resonances in the case of the Plutinos) and those on scattered eccentric orbits (which, for convenience, we will call scattered KBOs). The orbital characteristics of 1996TL$_{66}$ suggest that it is a scattered KBO. Objects in the classical Kuiper belt are on stable or weakly chaotic orbits and have managed to survive

Table 1 Orbital elements for 1996TL$_{66}$

	Nominal value	Uncertainty range
Semimajor axis (AU)	83.77	82.4–85.5
Eccentricity	0.581	0.57–0.59
Inclination (deg)	23.948	23.99–23.93
Longitude of ascending node (deg)	217.764	217.75–217.77
Argument of perihelion (deg)	182.59	174.7–187.4
Mean anomaly (deg)	358.54	360.3–357.6

These values are for epoch 1997 June 1.0, equinox 2000.0.

planetary perturbations over the age of the Solar System. The origin of the scattered population is more ambiguous. One possibility is that the scattered KBOs are Uranus–Neptune region planetesimals scattered by planetary embryos into large, eccentric orbits (as part of the process that formed the Oort cloud)[15–17]. Presumably, this scattered population would merge smoothly with the Oort cloud at larger distances[17]. An alternative scenario is that the scattered KBOs originated in the classical Kuiper belt, but have been scattered outwards by a transient population of large planetesimals[18] or by Neptune. In particular, those KBOs perturbed outward by Neptune could spend most of their lifetime trapped in various resonances, resulting in dynamical lifetimes comparable to the age of the Solar System[19]. Further observations of 1996TL$_{66}$ should help to constrain its origin further; for example, there is the possibility that 1996TL$_{66}$ actually lies in a resonance (for example, the 2 : 9 resonance at 82 AU)[20].

We note that some KBOs lost in previous surveys[8] may have been of the 1996TL$_{66}$ type. Objects that clearly have orbits of high inclination, but often completely indeterminate eccentricity, would be the best of such candidates. These might include 1994JV, 1994TH, 1995GJ and 1996KY$_1$, the available observations of which can easily be satisfied by TL$_{66}$-like orbits with $i \approx 12, 17, 17$ and 22 degrees, respectively. Such orbits might explain the failure to recover these objects a few months after their discoveries, although it is also possible that some non-recoveries were artefacts of poor seeing, poor transparency, and confusion with stars in the recovery attempts.

1996TL$_{66}$ provides the first direct evidence of a scattered planetesimal population between the currently known Kuiper belt (30–50 AU) and the Oort cloud (~10^4 AU). Although the origin of these scattered KBOs is still unknown, it is likely that these objects have, together, a substantial mass (2–8 times the mass of the present classical Kuiper belt). This suggests that the original solar nebula may have been more extensive and more massive than previously known. Whether the scattered KBOs originated in the Uranus–Neptune zone or the Kuiper-belt region, dynamical studies, constrained by observations of the current population of these objects, could provide valuable new information on the radial distribution of mass in the solar nebula. □

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Experimental evidence for non-exponential decay in quantum tunnelling

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An exponential decay law is the universal hallmark of unstable systems and is observed in all fields of science. This law is not, however, fully consistent with quantum mechanics and deviations from exponential decay have been predicted for short as well as long times[1–8]. Such deviations have not hitherto been observed experimentally. Here we present experimental evidence for short-time deviation from exponential decay in a quantum tunnelling experiment. Our system consists of ultra-cold sodium atoms that are trapped in an accelerating periodic optical potential created by a standing wave of light. Atoms can escape the wells by quantum tunnelling, and the number that remain can be measured as a function of interaction time for a fixed value of the well depth and acceleration. We observe that for short times the survival probability is initially constant before developing the characteristics of exponential decay. The conceptual simplicity of the experiment enables a detailed comparison with theoretical predictions.

We consider the motion of ultra-cold atoms in an accelerating optical potential of the form $V_0\cos[2k_L x - k_L a t^2]$, where a is the acceleration, V_0 is the well depth, x is position in the laboratory frame, t is time and k_L is the laser wavenumber[9,10]. In the accelerating reference frame (x'), this potential becomes $V_0\cos(2k_L x') + Max'$ where M is the mass of the atom. The linear term in x' leads to an asymmetry in the potential wells. This 'washboard potential' is the same as for the condensed-matter system of an electron moving in a periodic lattice with a d.c. electric field. The periodic optical potential is created by the spatially varying field of a standing wave of light formed by two counter-propagating beams from a single-mode laser. The laser is tuned sufficiently far from atomic resonance so that spontaneous scattering can be neglected, and the atom remains in the ground state. The standing wave is accelerated by ramping the frequency difference of its two beams.

In our previous work on quantum transport of atoms in an accelerating potential, we performed a spectroscopic study of the band structure and observed Wannier–Stark ladder resonances[11]. In parallel to our work, Bloch oscillations of ultra-cold atoms were also directly observed[12]. Those experiments were done in a regime where tunnelling from the trapped state was negligible. Recently we studied the tunnelling process for larger accelerations, and showed that it is the ultimate limit for this atom accelerator[13]. The trapped state can be considered an unstable quantum system that decays into a reservoir. This can be seen in the 'washboard potential' of the co-moving frame: an atom, trapped in one of the wells, escapes via tunnelling to the continuum. The predicted deviation from exponential decay for short times is related to the fact that the coupling between the system and reservoir is still reversible during that stage. Moreover, the decayed and undecayed state are not yet resolvable, even in principle. In the present system, it is not possible to tell whether an atom is still tracking the accelerating lattice for short times; only in longer times can this question by answered. By then, the decay is irreversible, leading to an exponential decay law. A significant improvement in the signal-to-noise ratio of the data has now enabled us to resolve the short-time tunnelling probability and to observe this phenomenon.

To trap and accelerate a significant number of atoms in a weak potential requires the initial source of atoms to be ultra-cold. We achieve this using a magneto-optic trap consisting of six intersecting

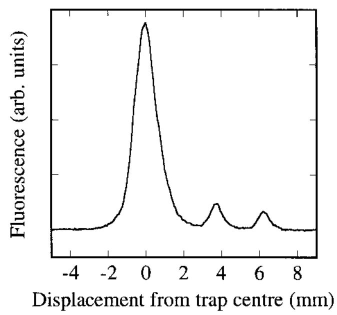

Figure 1 Distribution of atoms after exposure to a three-stage accelerating standing wave for $V_0/h = 80$ kHz. A small acceleration of 1,500 m s^{-2} was first imposed to trap atoms and separate them from the rest of the distribution. A large acceleration of 7,000 m s^{-2} was then turned on for a duration of 34 μs. During this stage atoms tunnel from the trapped state, and are lost to the accelerating potential. Finally the same small acceleration was imposed to separate the atoms that have survived from those that have tunnelled out. The duration of the three-step process is 1.5 ms, and the total switching time between the three stages is under 500 ns. A free drift of 3 ms allowed the surviving atoms to separate spatially from the main distribution.

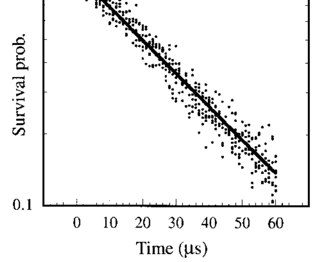

Figure 2 Typical example of experimentally measured survival probability for a small acceleration of 1,200 m s^{-2}, a large acceleration of 4,500 m s^{-2}, and $V_0/h = 50$ kHz as a function of the duration of the large acceleration. Note that the vertical axis is logarithmic. The solid line is a fit to an exponential.

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