LETTERS

A collisional family of icy objects in the Kuiper belt

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The small bodies in the Solar System are thought to have been highly affected by collisions and erosion. In the asteroid belt, direct evidence of the effects of large collisions can be seen in the existence of separate families of asteroids—a family consists of many asteroids with similar orbits and, frequently, similar surface properties, with each family being the remnant of a single catastrophic impact[1]. In the region beyond Neptune, in contrast, no collisionally created families have hitherto been found[2]. The third largest known Kuiper belt object, 2003 EL$_{61}$, however, is thought to have experienced a giant impact that created its multiple satellite system, stripped away much of an overlying ice mantle, and left it with a rapid rotation[3–5]. Here we report the discovery of a family of Kuiper belt objects with surface properties and orbits that are nearly identical to those of 2003 EL$_{61}$. This family appears to be fragments of the ejected ice mantle of 2003 EL$_{61}$.

Near-infrared reflectance spectroscopy has shown a diversity of surface compositions on Kuiper belt objects (KBOs), ranging from surfaces dominated by methane absorptions, to those with water-ice absorptions, to those with no discernible infrared spectral features[6]. Currently, the processes that create these diverse surfaces are not well understood. In an effort to better quantify the spectral signatures seen on KBOs, we obtained near-infrared reflectance surface spectra of 30 KBOs at the W.M. Keck observatory (see Supplementary Information for all spectra). Our survey confirms the three broad classes of KBO surface types: the largest KBOs—Pluto, Eris and 2005 FY$_9$—have spectra dominated by methane-ice absorption bands[7–9], while the remaining objects are either spectrally dominated by absorption features due to water ice at 1.5 and 2.0 μm wavelength or are featureless in the infrared to the level of noise.

Examination of the non-methane objects reveals that although most show moderate or no water-ice absorption, six KBOs (namely the extremely large KBO 2003 EL$_{61}$, plus the much smaller 1995 SM$_{55}$, 1996 TO$_{66}$, 2002 TX$_{300}$, 2003 OP$_{32}$ and 2005 RR$_{43}$), and also the brightest satellite of 2003 EL$_{61}$ (ref. 4), show extremely deep absorption features characteristic of water ice. In addition, the measured colours of the surfaces of these KBOs are exclusively neutral, compared to the wide range of optical colours seen in the other KBOs[10]. An examination of the depth of the water-ice absorption as a function of colour (Fig. 1, see Supplementary Discussion for details) shows that these objects form a unique group with surface characteristics different from the remaining objects. When these iciest KBOs are excluded, no further correlation is seen between water absorption depth and colour. Using the Kuiper variant of the Kolmogorov–Smirnov test, we calculate that the likelihood that the KBOs with deep water-ice absorptions were selected from the same colour distribution as the remaining population is less than 1.2%.

As well as their surface characteristics suggesting similarities between the objects, the objects themselves are also clustered within an exceedingly small dynamical region of the Kuiper belt (Fig. 2). To more accurately examine the dynamical relationships between the objects, we determined their proper orbital elements by taking 50-Myr averages of their osculating orbital elements (see Supplementary Discussion). The proper elements differ by only a few per cent from each other: the semimajor axes (a) of the six objects with deep water-ice absorptions have a spread of 2.15 AU ($\Delta a/a \approx 0.05$), the eccentricities differ by 0.08, and the inclinations differ by 1.4° (0.02 rad). Four of these objects are even more tightly clustered, with differences of only 0.1 AU in semimajor axis, 0.03 in eccentricity, and 1.0° in inclination. These six objects have the smallest dispersion of any sample of six within our survey. The probability of randomly selecting the single most clustered set of six out of a sample of 32 is only 1×10^{-6}.

The similar surface characteristics and extremely small dynamical dispersion of these objects are naturally explained if all six KBOs were derived from a single disruptive collision. The largest of this group of KBOs, 2003 EL$_{61}$, has a mass that is probably of the order of 100 times more than the mass of the other five objects combined (assuming that the objects all have a similar albedo, which their similar surface characteristics suggest is reasonable, and that all of the objects have the same density, which must be correct within a factor of three). 2003 EL$_{61}$ is thus the most plausible candidate for the remnant of the progenitor of this collisional family. Moreover, the fast rotation, multiple satellite system, and high density of 2003 EL$_{61}$ have previously been argued to be due to a giant impact that ejected a fraction of the original icy mantle and left two satellites behind[3,4]. The discovery of a family of objects with very similar orbits to 2003 EL$_{61}$ and with very similar surface properties to 2003 EL$_{61}$ and its satellite

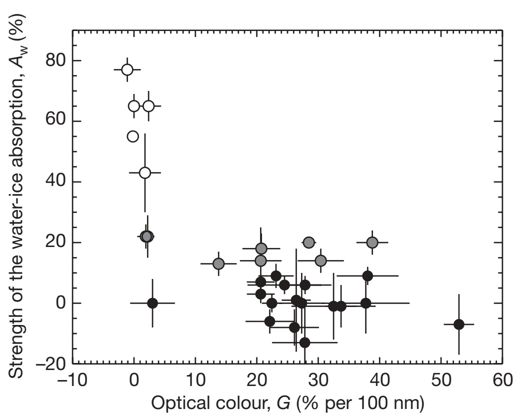

Figure 1 | The strength of the infrared water-ice absorption feature versus optical colour for all KBOs in our survey and those with published spectra. See Supplementary Information for the complete list of objects. The strength of the water-ice absorption feature, A_w, is defined as the fractional absorption at 2.0 μm compared to the reflectance at 1.8 μm. The optical colour, G, is defined as the fractional change in reflectance per 100 nm wavelength change between 0.5 and 0.8 μm. Six KBOs (open circles) appear clustered with large water-ice absorptions and neutral colours. The black dots indicate objects with absorption depth, A_w, less than 10%; the grey dots represent objects with A_w less than 30%. The white dots represent objects with A_w greater than 30%. Error bars are 1σ.

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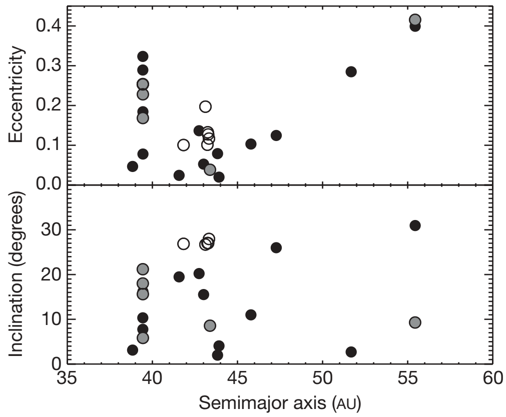

Figure 2 | The proper eccentricity and inclination of KBOs in our sample as a function of semimajor axis. The distributions in eccentricity and inclination of our population reflect the general distribution seen in the Kuiper belt. The black dots indicate objects with absorption depth, A_w, less than 10%; the grey dots represent objects with A_w less than 30%. The white dots represent objects with A_w greater than 30%. Four scattered objects with semimajor axes between 95 and 103 AU have been excluded so that the general distribution is clearly illustrated. The objects with the strongest water-ice absorption have clustered orbital parameters.

strongly argues that these family members are the dispersed remnants of the mantle of the proto-2003 EL_{61}.

To examine more closely whether the observed orbits could indeed result from collisional disruption, we construct a simple model of the aftermath of a dispersive collision by calculating the new orbital elements of test particles ejected from the dispersion of a proto-2003 El_{61}. We assume that the collision occurred as the proto-2003 EL_{61} crossed the ecliptic, where KBO number densities are the highest, and that, of the two ecliptic crossings in an inclined orbit, the impact occurred at the crossing at the higher-density portion of the Kuiper belt. The observed spread in orbital elements can be explained with ejection velocities of approximately 400 m s^{-1} (see Fig. 3). However, such velocities suggest that fragments should be strewn throughout a wide swath of the Kuiper belt, rather than confined to the small dynamical region observed. Although it is clear that the high-inclination population of the Kuiper belt is relatively unexplored and that many more fragments are likely to be eventually found, it appears improbable that the only fragments known would be so tightly clustered if such a large velocity dispersion occurred. In contrast, the orbital elements of all but one of the fragments can be explained by assuming that the centre of the tight cluster of four objects defines the centre of the collision, and that the collision dispersed objects with a velocity of only ~140 m s^{-1} above the primary escape velocity.

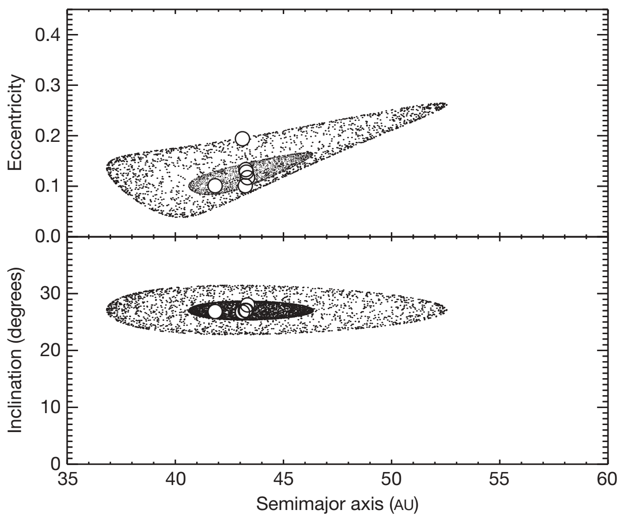

Figure 3 | Simulations of the dispersion in orbital elements expected after the ejection of fragments in a giant impact. The open circles give the current proper orbital elements of the fragments. The widely dispersed small dots show orbital elements expected from a dispersive velocity of 400 m s^{-1} and a dispersion centred on the average position of the fragments. Although this velocity can explain each of the known fragments, it also predicts that fragments should be strewn throughout a much larger region of the Kuiper belt. The more tightly concentrated dots show orbital elements expected from a dispersive velocity of 140 m s^{-1} and a dispersion centred on the average position of the central four KBOs. Five of the six fragments can be explained by this much smaller velocity. 2003 EL_{61}, the only object not fitted by this smaller velocity, is in a mean-motion resonance with Neptune that is capable of raising its eccentricity to its current value.

In this case, however, the single object that does not fit within the small velocity dispersion is 2003 EL_{61}, which still requires a velocity of ~400 m s^{-1} to explain its slight displacement in eccentricity from the remainder of the family. Long-term integration of the orbit of 2003 EL_{61} shows, however, that this object (and only this object) has large excursions in eccentricity over time owing to chaotic diffusion within the 12:7 mean-motion resonance with Neptune[11,12]. To explore this possibility, we integrated the orbits of 32 test particles with proper orbital elements within 0.3 AU in semimajor axis, 0.025 in eccentricity, and 0.5° in inclination from the centre of the cluster. We find that 5 of the 32 test particles diffuse out of the small initial region of the family and into higher-eccentricity orbits. All five of the test particles that diffused out appeared to be caught in the same 12:7 resonance that 2003 EL_{61} occupies. We thus suggest that 2003 EL_{61} was initially part of the extremely tightly clustered group of objects and that the initial collision placed it within the nearby 12:7 resonance, which subsequently raised the eccentricity to its current value.

Although the spectral and dynamical similarities of the objects argue for a common origin, and the rapid rotation, high density, and multiple satellite system of 2003 EL_{61} argue for a collisional history, some aspects of the system differ from general expectations. In general, models of the aftermath of collisions suggest that highly energetic impacts can either disrupt and disperse the primary or lead to the creation of a disk or satellite[13–17]. Simultaneous creation of both dispersed fragments and multiple satellites has not been seen. In addition, the 140 m s^{-1} dispersion between the objects is smaller than expected; simulations of disruptive impacts suggest that fragments are ejected with moderate fractions of the parent escape velocity[14,18], which would imply a dispersion a factor of three or more higher. Detailed simulations of collisions, however, show that a variety of outcomes are possible, depending on impact energies, impact angles, and compositions and initial spins of both bodies[17,19]. We can make a first-order estimate of the impactors involved by making plausible assumptions about the initial bodies. If the proto-2003 EL_{61} had a density of 2.0 g cm^{-3} (similar to that of Pluto, Triton, Eris and Charon, the only other Kuiper-belt-derived bodies of comparable size with known density), and the collision removed sufficient water ice to change the density to the current value of 2.6 g cm^{-3}, then the proto-2003 EL_{61} was a body of radius ~830 km, and ~20% of the initial mass was removed in the collision. At typical ecliptic encounter velocities of ~3 km s^{-1}, models suggest that a collision with an object 60% of the radius of the proto-2003 EL_{61} would cause such a moderate level mass removal[14]. For lower-velocity impacts, which may be required to explain the low velocity dispersion of the fragments, even larger impactors are required.

Finally, we consider the connection between a dispersive impact and the deep water-ice absorption. Although it is tempting to suggest that the deep water-ice absorption is a function of a relatively short surface exposure age for these objects, implying a relatively recent collision, little is understood about causes of spectral variations in KBOs. We note, however, that the deep water-ice absorptions are consistent with a relatively pure water-ice composition, as might be expected from fragments that are the remnants of a dispersed icy mantle. In the end, however, we use the deep water-ice absorptions only as tracers of a common origin rather than as indications of a specific process related to an impact. It is possible that the currently recognized fragments are all from a similar region of the parent body, and that additional fragments with a variety of spectral signatures may some day be found.

Previous attempts to identify families of collisional fragments within the Kuiper belt using purely dynamical arguments, such as those usually used to identify asteroid belt families, have given generally ambiguous results[20]. The dual spectroscopic and dynamical approach used here, combined with the earlier suggestion that the largest member of this family independently shows signs of having experienced a giant impact, provides overwhelming circumstantial evidence for the identification of this collisional family.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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