

Discovery of an Icy Collisional Family in the Kuiper Belt

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The bodies beyond Neptune, collectively known as Kuiper belt objects (KBOs), are thought to have been highly affected by collisions and erosion, but little direct evidence of such processes remains today. Through an infrared spectroscopic survey of KBOs, we have discovered a subclass of objects with spectral and orbital properties similar to the third largest known KBO, 2003 EL61. 2003 EL61 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 rotation¹⁻³. This new subclass of objects appears to be fragments of the ejected ice mantle, and we show that the similarities in the spectra and orbits could be a natural outcome of a giant impact. This collisional family of 2003 EL61 provides a new window into the physical, dynamical, and chemical effects of giant impacts in the solar system.

Near-infrared reflectance spectroscopy has shown a diversity of surface compositions on KBOs, from surfaces dominated by methane absorptions, to those with water ice absorptions, to those with no discernible infrared spectral features⁴. 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 supplemental information for all spectra). Our survey confirms the three broad classes of KBO surface types: the largest KBOs, Pluto, 2003 UB313, and 2005 FY9, have spectra dominated by methane ice absorption bands similar to those seen on Pluto⁵⁻⁷, while the remaining objects are either spectrally dominated by absorption features due to water ice at 1.5 and 2.0 μm or are featureless in the infrared to the level of noise.

Examination of the non-methane objects reveals that while most objects show moderate or no water ice absorption, six KBOs, the extremely large KBO 2003 EL61, plus

the much smaller 1995 SM55, 1996 TO66, 2002 TX300, 2003 OP32, and 2005 RR43, and also the brightest satellite of 2003 EL61², show extremely deep water ice absorption features. 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 KBOs⁸. An examination of the depth of the water ice absorption as a function of colour (figure 1, see Supplemental Discussion for details) shows that these objects form a group with surface characteristics unique 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%.

While the surface characteristics suggest similarities between the objects, the objects themselves are additionally clustered within an exceedingly small dynamical region of the Kuiper belt (Figure 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 Supplemental Discussion). We find that their proper orbital elements are clustered even more strongly than the osculating elements. The proper elements differ by only a few percent from each other: the semimajor axes of the six objects with deep water ice absorptions have a spread of 2.15 AU ($\Delta a/a \sim 0.05$), the eccentricities differ by 0.08, and the inclinations differ by 1.4 degrees (0.02 radians). 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 degrees in inclination. While it is impossible to rigorously quantify the probability that any six randomly selected objects in our spectral sample would be dynamically clustered, these six objects have the smallest dispersion of is only 4×10^{-7} .

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 EL61, has a mass that is likely of order 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 suggests is reasonable, and that all of the objects have the same density, which must be correct within a factor of several). 2003 EL61 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 EL61 have previously been argued to be due to a giant impact which ejected a fraction of the original icy mantle and left two satellites behind^{1,2}. The discovery of a family of objects with very similar orbits to 2003 EL61 and with very similar surface properties to 2003 EL61 and its satellite strongly argues that these family members are the dispersed remnants of the mantle of the proto-2003 EL61.

To more closely examine whether the observed orbits could indeed result from collisional disruption, we construct a simple model of a dispersive collision by calculating the new orbital elements of test particles ejected from the dispersion of a proto-2003 EL61. We assume that the collision occurred as the proto-2003 EL61 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 Figure 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. While 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 $\sim 140 \text{ m s}^{-1}$ above the primary escape velocity. In this case, however, the single object that does not fit within the small velocity dispersion is 2003 EL61, which still requires a velocity of $\sim 400 \text{ m s}^{-1}$ to explain its slight displacement in eccentricity from the remainder of the family. Long term integration of the orbit of 2003 EL61 shows, however, that this object (and only this object) can have large excursions in eccentricity over time due to chaotic diffusion within the 12:7 mean-motion resonance with Neptune⁹. More importantly, the entire collisional family is close to the edge of instability, and some members may diffuse outward in eccentricity over time¹⁰. 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 degrees 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 EL61 occupies. We thus hypothesize that 2003 EL61 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.

While 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 EL61 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 creation of a disk or satellite¹¹⁻¹⁵. 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^{12,16}, which would imply a dispersion a factor of several higher. While such cases have not been specifically modelled, we hypothesize that the low velocity dispersion of the fragments combined with the retained satellites suggests the possibility of an impact with parameters near the transition between energetic dispersion of fragments and satellite retention. If we assume that the initial body had a Pluto-like density of 1.9 g cm^{-3} and that the collision removed sufficient water ice to change the density to the current value of 2.6 g cm^{-3} , the proto-2003 EL61 was a $\sim 870 \text{ km}$ radius body and $\sim 20\%$ of the initial mass was removed in the collision. Such collisions require less energy than the fully disruptive collisions usually considered^{11,12}, but models suggest that a collision with an object 60% of the radius of 2003 EL61 would cause such a moderate level mass removal¹². Detailed simulations of collisions show that a variety of outcomes are possible depending on impact energies, impact angles, and compositions and initial spins of both bodies^{15,17}.

Finally, we consider the connection between a dispersive impact and the deep water ice absorption. While it is tempting to suggest that the deep water ice absorption is a function of a relatively short surface exposure age for these objects and thus 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 a tracer of a common origin rather than an indication 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 results¹⁸. 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 that the identification of the collisional family and the largest remaining remnant in this case is secure. 2003 EL61, its two satellites, and its family of collisional remnants provide a new window into the physical, dynamical, and chemical effects of giant impacts in the solar system.

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Acknowledgements: The authors would like to thank Re'em Sari, Bill McKinnon, Keith Noll, and Tom Ahrens for their comments on this work. This research is supported by a grant to M.E.B. from NASA Planetary Astronomy.

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Figure 1. The fractional water ice absorption depth, A_w , versus visible colour gradient, G , for KBOs in our survey and all KBOs with published spectra (see supplemental information for the complete list of objects). A_w is defined as the fraction absorption at $2.0 \mu\text{m}$ compared to the reflectance at $1.8 \mu\text{m}$. G is defined as the fractional change in reflectance per 100 nm. A single gradient can generally characterize the reflectance spectra of KBOs between $.5$ and $.8 \mu\text{m}$, where few absorption features have been observed. Five KBOs appear clustered with large water ice absorptions and neutral colors.

Figure 2. The osculating eccentricity and inclination of KBOs in our sample as a function of semi-major axis. The distributions in eccentricity and inclination of our population reflect the general distribution seen in 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% and 2003 EL61 is shown by the white box. Four scattered objects with semi-major axes between 95 AU and 103 AU have been excluded so that the

general distribution is clearly illustrated. We find that the objects with the strongest water ice absorption have clustered orbital parameters. We roughly quantified the clustering by measuring the variance in the orbital parameters given by $\sigma = \sqrt{\sigma(e)^2 + \sigma(i/2)^2 + \sigma(a/\bar{a})^2}$, where e , i , and a are the eccentricity, the inclination in radians, and the semi-major axis respectively. We calculated σ for all possible combinations of six objects in our sample and find that the probability that any set has as similar orbital elements as the six with the highest A_w is 4×10^{-7} , suggesting that the clustering in orbital parameters is not by chance.

Figure 3. Simulations of the dispersion in orbital elements expected after the ejection of fragments in a giant impact. The black diamonds give the current proper orbital elements of the fragments. The widely dispersed 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. While 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 EL61, the only object not fit by this smaller velocity, is in a mean motion resonance with Neptune that is capable of raising its eccentricity to its current value. (Note to reviewers: this figure does not always view correctly on computer screens, but seems to work when printed)