The Astrophysical Journal, 684: L107–L109, 2008 September 10

DETECTION OF ADDITIONAL MEMBERS OF THE 2003 EL61 COLLISIONAL FAMILY VIA NEAR-INFRARED SPECTROSCOPY

E. L. Schaller and M. E. Brown
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125; schaller@caltech.edu
Received 2008 July 13; accepted 2008 August 1; published 2008 August 22

ABSTRACT

We have acquired near-infrared spectra of Kuiper Belt objects 2003 UZ117, 2005 CB79, and 2004 SB60 with NIRC on the Keck I telescope. These objects are dynamically close to the core of the 2003 EL61 collisional family and were suggested to be potential fragments of this collision by Ragozzine and Brown. We find that the spectra of 2003 UZ117 and 2005 CB79 both show the characteristic strong water ice absorption features seen exclusively on 2003 EL61, its largest satellite, and the six other known collisional fragments. In contrast, we find that the near-infrared spectrum of 2004 SB60 is essentially featureless with a fraction of water ice of less than 5%. We discuss the implications of the discovery of these additional family members for understanding the formation and evolution of this collisional family in the outer solar system.

Subject headings: infrared: solar system — Kuiper Belt

1. INTRODUCTION

The only known collisional family in the Kuiper Belt was detected because of the unique spectral properties the family members (Brown et al. 2007). The near-infrared spectra of all other non-volatile-rich Kuiper Belt objects (KBOs) lie on a continuum between those whose spectra contain moderate amounts of water ice absorptions to those whose spectra are essentially featureless (Brown et al. 2007; Barkume et al. 2008). In contrast, the near-infrared spectra of 2003 EL61, its largest satellite, and five other small KBOs resemble laboratory spectra of pure crystalline water ice (Brown et al. 1999, 2007; Barkume et al. 2006, 2008; Trujillo et al. 2007; Merlin et al. 2007). Remarkably, these objects are also relatively clustered in orbital element space. The largest object, 2003 EL61, had been previously suggested to have experienced a massive collision that imparted its fast (4 hr) rotation, stripped off most of its icy mantle leaving it with a density close to rock (2.7 g cc^{-1}), and formed its two satellites (Rabinowitz et al. 2006; Brown et al. 2006; Lacerda et al. 2008). Brown et al. (2007) concluded that the four extremely water-ice-rich KBOs and the large satellite of 2003 EL61 were in fact fragments of the icy mantle of the proto–2003 EL61 that had been ejected during a massive collision.

While collisional families in the asteroid belt can be identified by their dynamical clustering alone, families in the Kuiper Belt are much harder to identify because the collisional ejection velocities can be a significant fraction of an object's orbital velocity. Collisional fragments can therefore be spread out over a wide range of orbital element space with the fastest ejected fragments having significantly different orbits from the family core. The 2003 EL61 family members were all identified on the basis of their unique surface properties: they are the only known objects in the Kuiper Belt with extremely pure water ice spectra and neutral visible colors. It is only because of this unique surface signature that detection of the 2003 EL61 family members was possible.

In order to determine if other known KBOs could be fragments of the 2003 EL61 collision, Ragozzine & Brown (2007) integrated the orbits of 131 high-inclination KBOs to determine their proper orbital elements and minimum ejection velocities away from the 2003 EL61 family core. They determined the minimum ejection velocity a KBO must have had in order to reach its present orbit from the modeled location of the family-forming impact. In Figure 1 we show object H magnitude versus minimum ejection velocity (from Ragozzine & Brown 2007) for the known KBOs closest to the family core. For KBOs in known resonances, we plot the ejection velocity accounting for resonance diffusion (Ragozzine & Brown 2007). A large fraction of these objects have never been observed to determine if they have IR spectral signatures consistent with the 2003 EL61 family members. It is important to note that although all of the known 2003 EL61 family members have neutral visible colors, visible color or visible spectroscopy alone (Pinilla-Alonso et al. 2008) is not sufficient for family member identification. There are many KBOs with neutral visible colors that do not also have strong water ice absorptions and are not members of the 2003 EL61 collisional family. Therefore, while visible colors can be used to rule out objects as potential family members, near-infrared spectroscopy to determine water ice absorption depths is necessary for definitive family member identification.

Identifying additional family members and characterizing the extent of the spread of fragments throughout the Kuiper Belt may provide insight into the physics of this giant impact event in the outer solar system. In this Letter we present near-infrared spectra obtained with the Keck I telescope of KBOs 2003 UZ117, 2005 CB79, and 2004 SB60, objects that are located 67, 97, and 221 m s^{-1} away from the modeled 2003 EL61 family core, respectively (Fig. 1). KBOs 2003 UZ117 and 2005 CB79 were suggested to be the most likely additional family candidates by Ragozzine & Brown (2007).

2. OBSERVATIONS AND RESULTS

Observations of 2003 UZ117, 2005 CB79, and 2004 SB60 were performed with the Near Infrared Camera (NIRC) on the Keck I telescope. Objects were identified in the field by their motion relative to the background stars. Targets were moved to the center of a 0.525″ wide slit and were then observed with either a J through H order sorting filter and a 120 line mm^{-1} grism (2003 UZ117 and 2005 CB79) or an H through K order sorting filter and a 150 line mm^{-1} grism (2004 SB60). In all cases, exposure times for the individual spectra were 200 s. Targets were dithered along the slit in a five-position nod pat-

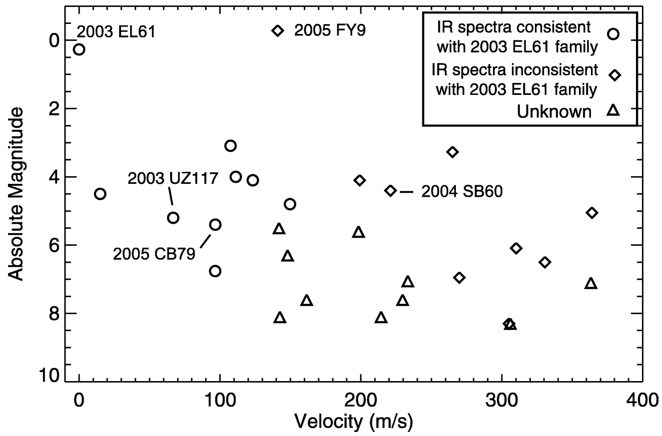

FIG. 1.—Kuiper Belt object absolute magnitude (H) vs. the minimum velocity required for a given KBO to reach its orbit from the modeled 2003 EL61 family forming collision (from Ragozzine & Brown 2007, Tables 1 and 2). Including 2003 UZ117 and 2005 CB79 (this Letter), all of the objects within ∼130 m s^{-1} have similar infrared spectra showing extremely deep absorptions due to water ice on their surfaces. These are the only KBOs with such strong absorption features. 2004 SB60 was found to have a featureless infrared spectrum inconsistent with the other 2003 EL61 family members.

tern with 5″ between each dither. During observations the telescope tracked at each target's predicted rate of motion.

2.1. *2003 UZ117 and 2005 CB79*

Low-resolution spectral observations in the H–K (1.4–2.5 μm) region are ideal for determining the presence or absence of water ice due to two broad water ice absorption features centered at 1.5 and 2.0 μm (Fig. 2). Barkume et al. (2008) observed 45 KBOs and centaurs in this wavelength range and parameterized all spectra with a two-component model consisting of crystalline water ice covering a fraction of the surface, f, mixed linearly with dark continuum component with slope m, covering $1 - f$ of the surface. They solved for m and f in each spectrum by using a least-squares minimization scheme using the Powell method. Family members clearly stood out because of their high fractions of water ice ($f > 0.8$) in this parameterization compared with all other objects in the survey ($f < 0.5$).

Low-resolution spectral observations at H–K with NIRC are only practical for objects with visual magnitudes less than ∼21. Spectral observations in the J–H region of the spectrum (1.1–1.6 μm) allow us probe the spectra of objects (visual magnitude ∼ 21.5) that would be too faint to detect or obtain sufficient signal to noise in a reasonable amount of time with H–K spectroscopy. Fortunately, the water ice absorption feature centered at ∼1.5 μm is perfectly suited for detection with J–H spectroscopy. We can therefore observe KBOs up to half a magnitude fainter than previous observations in H–K (Barkume et al. 2008), allowing us to detect strong water ice absorptions and determine if these smaller objects are also members of the 2003 EL61 collisional family.

J–H spectra of two dynamically likely family members, 2003 UZ117 and 2005 CB79 (visual magnitudes of 21.3 and 21.2, respectively) were obtained. KBO 2003 UZ117 was observed on 2007 September 23 UT for a total integration time of 4000 s; 2005 CB79 was observed on 2007 May 21 and 22 UT for a total integration time of 12,200 s. Nearby G-type main-sequence stars were observed within 0.1 air mass of the targets for telluric calibration. Variable seeing, sky conditions, and occasionally poor tracking (especially on the 2005 CB79 observations) caused the individual spectra of each of the KBOs to be of varying quality, thus only the highest signal-to-noise spectra were included and the rest discarded for this analysis. The final spectra consist of total integration times of 2800 s for 2003 UZ117 and 5200 s for 2005 CB79. Spectral data reduction was carried out using standard procedures as described in Brown (2000) and Barkume et al. (2008).

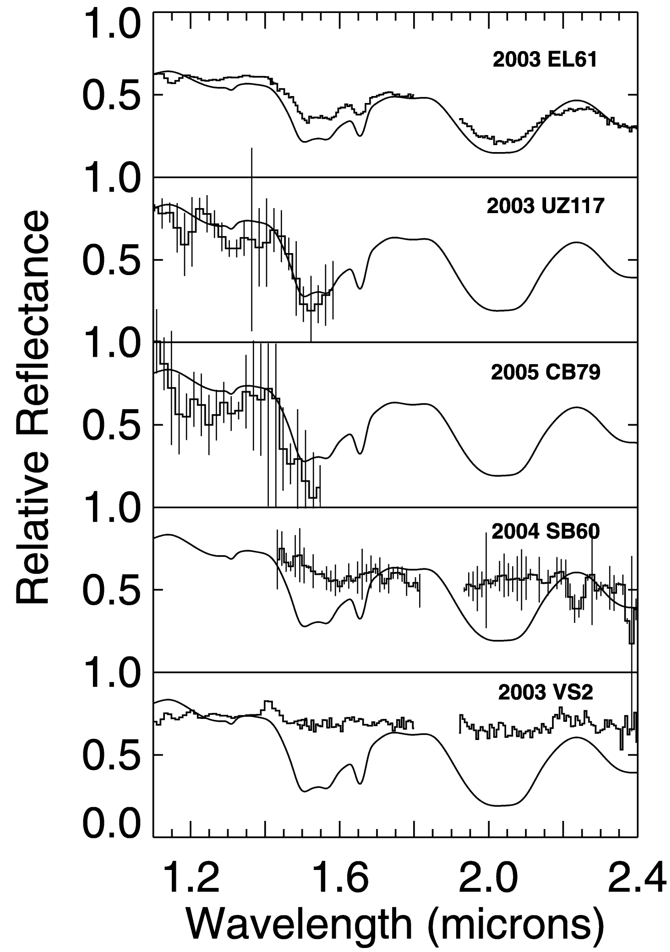

FIG. 2.—Near-infrared spectra of 2003 EL61 and its collisional family members show strong signatures of nearly pure water ice on their surfaces. Shown are the spectra of five KBOs along with a pure crystalline water ice model (Grundy & Schmitt 1998). We observed KBOs 2003 UZ117, 2005 CB79, and 2004 SB60, objects 67, 97 and 221 m s^{-1} away from the modeled 2003 EL61 family core (Ragozzine & Brown 2007), to determine if their near-infrared spectra contained the characteristic strong water ice absorptions. Spectra of 2003 UZ117 and 2005 CB79 show strong absorptions at 1.4–1.6 μm consistent with the presence of high fractions of water ice on their surfaces. In contrast, the spectrum of 2004 SB60 is essentially featureless. The flat spectrum of 2003 VS2 (from Barkume et al. 2008), a typical non-family-member KBO, is shown for comparison.

The final 2003 UZ117 and 2005 CB79 spectra were each binned over 4 pixels to increase the signal to noise per pixel. We used a Gaussian weighting function with a FWHM of 8 pixels resulting in oversampled spectra with a spectral resolution of ∼33. In Figure 2 we show these spectra with 1 σ error bars along with a model of pure water ice with 50 μm grain sizes at 50 K (Grundy & Schmitt 1998). We can quantitatively parameterize the amount of water ice using the same spectral model as Barkume et al. (2008) but considering the wavelength region from 1.1–1.6 μm. Using a Powell minimization scheme to solve for the best fit of the parameters m and f, we find that the spectra of 2003 UZ117 and 2005 CB79 are fit by water ice fractions of 0.92 ± 0.16 and 1.02 ± 0.10, respectively. The high fraction of water ice given by this parameterization for 2005 CB79 may be due to the fact that the water ice grain sizes on this object are somewhat larger than those modeled by Barkume et al. (2008). Nonetheless, the deep absorptions detected from ~1.4 to 1.6 μm on 2003 UZ117 and 2005 CB79 are clearly consistent with a high fraction of water ice (in contrast with all other known KBOs) but comparable to the other 2003 EL61 family members (Barkume et al. 2008).

2.2. *2004 SB60*

KBO 2004 SB60, with a visual magnitude of 20.8, was bright enough to be observed in *H–K*. We observed it on 2007 September 23 for a total integration time of 3000 s. Data reduction was carried out as described above. A nearby G-type main-sequence star was observed at similar (within 0.03) air mass of the target. Division of the 2004 SB60 spectrum by the star spectrum allowed us to calibrate telluric features. The resulting spectrum has a resolution $r \sim 160$.

Using the same spectral parameterization of Barkume et al. (2008) and described above, we find that the fraction of water ice in the spectrum of 2004 SB60 is consistent with 0 and can be no more than 0.05 (Fig. 2). The low water ice fraction seen in the spectrum of 2004 SB60 is similar to that seen in many small KBOs (see Barkume et al. 2008). The spectrum of 2004 SB60 is clearly not consistent with the other members of the 2003 EL61 collisional family that have water ice fractions greater than 0.8 (Fig. 2).

3. DISCUSSION

KBOs 2003 UZ117 and 2005 CB79 contain high fractions of pure water ice on their surfaces and appear dynamically related to the other members of the 2003 EL61 collisional family. We therefore conclude that they are members of this collisional family. Thus far, all objects within 130 m s^{-1} of the modeled collision center (Ragozzine & Brown 2007) have been shown to have the same unique strong water ice spectral signatures. KBO 2004 SB60, at 221 m s^{-1} from the family core, has an essentially featureless spectrum inconsistent with 2003 EL61 and its family members but comparable to many other small KBOs. The flat spectrum we observed is consistent with infrared photometric observations of 2004 SB60 with *HST* by Stephens & Noll (2007). Infrared spectral or spectrophotometric observations of more potential fragments with minimum ejection velocities from ~150 to ~300 m s^{-1} could help constrain the extent to which fragments were scattered throughout the Kuiper Belt and could tell us about the physics of the giant impact itself. In addition to the distribution of fragments, any collisional model would also need to explain the presence of the two satellites of 2003 EL61.

Although it does not have the spectral signature of the fragments of the 2003 EL61 collision, 2004 SB60 is an interesting object in its own right. Noll et al. (2008) have found this object to be one of the few high-inclination small binary objects in the Kuiper Belt. It is worth noting the possibility that not all fragments of the 2003 EL61 collision necessarily have the unique strong water ice signature. Fragments from different locations in the initial parent body may have had different initial compositions. However, without this unique spectral signature, identification of an object as a family member is currently impossible.

Another object near the center of the 2003 EL61 family is the third largest KBO, 2005 FY9, which has a velocity closer to the center of the collision (150 m s^{-1}) than one of the known fragments but has a spectrum dominated by methane, not water ice absorptions. We find it intriguing that two of the largest KBOs are so close to each other in orbital element space but can think of no reason why they should be physically related.

The spectral signature of extremely pure water ice found on 2003 EL61 and its fragments and nowhere else in the Kuiper Belt is the only reason definitive identification of the collisional family was possible. A collision with a non-differentiated parent body would likely not produce such a distinct spectral signature in its fragments. Future large-scale surveys of the Kuiper Belt such as Pan-STARRS and LSST are expected to increase the numbers of known KBOs by over an order of magnitude. With higher numbers of objects, overdensities in certain regions may be revealed and families without unique spectral signatures may be able to be identified by their dynamics alone.

We thank an anonymous referee for a helpful review. This research is supported by NASA Planetary Astronomy grant NNG05GI02G. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

REFERENCES

Barkume, K. M., Brown, M. E., & Schaller, E. L. 2006, ApJ, 640, L87
———. 2008, AJ, 135, 55
Brown, M.E. 2000, AJ, 119, 977
Brown, M. E., Barkume, K. M., Ragozzine, D., & Schaller, E. L. 2007, Nature, 446, 294
Brown, M. E., et al. 2006, ApJ, 639, L43
Brown, R. H., Cruikshank, D. P., & Pendleton, Y. 1999, ApJ, 519, L101
Grundy, W. M., & Schmitt, B. 1998, J. Geophys. Res., 103, 25809
Lacerda, P., Jewitt, D., & Peixinho, N. 2008, AJ, 135, 1749
Merlin, F., Guilbert, A., Dumas, C., Barucci, M. A., de Bergh, C., & Vernazza, P. 2007, A&A, 466, 1185
Noll, K. S., Grundy, W. M., Stephens, D. C., Levison, H. F., & Kern, S. D. 2008, Icarus, 194, 758
Pinilla-Alonso, N., Licandro, J., & Lorenzi, V. 2008, preprint (arXiv:0807.2670)
Rabinowitz, D. L., Barkume, K., Brown, M. E., Roe, H., Schwartz, M., Tourtellotte, S., & Trujillo, C. 2006, ApJ, 639, 1238
Ragozzine, D., & Brown, M. E. 2007, AJ, 134, 2160
Stephens, D. C., & Noll, K. S. 2007, BAAS, 38, 491
Trujillo, C. A., Brown, M. E., Barkume, K. M., Schaller, E. L., & Rabinowitz, D. L. 2007, ApJ, 655, 1172