The Astrophysical Journal, 639:L43–L46, 2006 March 1

SATELLITES OF THE LARGEST KUIPER BELT OBJECTS

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Received 2005 October 2; accepted 2006 January 23; published 2006 February 10

ABSTRACT

We have searched the four brightest objects in the Kuiper Belt for the presence of satellites using the newly commissioned Keck Observatory Laser Guide Star Adaptive Optics system. Satellites are seen around three of the four objects: Pluto (whose satellite Charon is well-known and whose recently discovered smaller satellites are too faint to be detected), 2003 EL61 (where a second satellite is seen in addition to the previously known satellite), and 2003 UB313 (where a satellite is seen for the first time). The object 2005 FY9, the brightest Kuiper Belt object (KBO) after Pluto, does not have a satellite detectable within 0″.4 with a brightness of more than 1% of the primary. The presence of satellites around three of the four brightest KBOs is inconsistent with the fraction of satellites in the Kuiper Belt at large at the 99.2% confidence level, suggesting a different formation mechanism for these largest KBO satellites. The two satellites of 2003 EL61, and the one satellite of 2003 UB313, with fractional brightnesses of 5% and 1.5%, and 2%, of their primaries, respectively, are significantly fainter relative to their primaries than other known KBO satellites, again pointing to possible differences in their origin.

Subject headings: Kuiper Belt — planets and satellites: general — techniques: high angular resolution

Online material: color figure

1. INTRODUCTION

The discovery and orbital characterization of satellites around objects in the Kuiper Belt has provided us with a unique window into the early history of the outer solar system. The early discovery of Charon (Christy & Harrington 1978) around Pluto and the high angular momentum of the Pluto-Charon system led to the hypothesis that a giant impact was responsible for formation of the system (McKinnon 1989), suggesting, even before the discovery of the remainder of the Kuiper Belt, that many more objects might exist in the regions beyond Neptune. It was generally expected that satellites around smaller Kuiper Belt objects (KBOs), if they existed, would form through the same mechanism and would consequently be on tightly bound circular orbits. The discovery of the first satellite around the smaller Kuiper Belt object 1998 WW31, with a satellite separation of almost 3 times the separation of Pluto and Charon and with a highly eccentric orbit, was thus quite a surprise (Veillet et al. 2002). The large semimajor axis of the 1998 WW31 system leads to an even more specific angular momentum than the Pluto-Charon system. The angular momentum is significantly more than can be explained from impact formation, leading to the suggestion of a capture origin (Goldreich et al. 2002). Subsequent discoveries of KBO satellites and the determination of their orbits have found that most, so far, resemble the 1998 WW31 system (Osip et al. 2003; Noll et al. 2004a, 2004b). The Pluto system, perhaps because of its size, has been the only system for which an entirely different formation mechanism has seemed necessary. The recent discovery of two possible additional satellites around Pluto makes Pluto seem even more of a special case.

With the recent discovery of several KBOs approaching (and even exceeding) the size of Pluto, a systematic search for satellites in these largest systems will help us determine whether the Pluto system remains unique or not. The Keck Observatory Laser Guide Star Adaptive Optics (LGS AO) system is capable of delivering near–diffraction-limited resolution at the K band (2.1 μm) for targets with magnitudes $V < 18$ (Wizinowich et al. 2006). A partial aberration correction can be obtained for a target up to a magnitude fainter (van Dam et al. 2006). We present a survey of the four currently known objects in the Kuiper Belt that are bright enough that they can be imaged at high resolution using the LGS AO system of the Keck Observatory.

2. OBSERVATIONS

The four brightest known objects in the Kuiper Belt, Pluto, 2005 FY9, 2003 EL61, and 2003 UB313, with V magnitudes of 14.0, 16.8, 17.5, and 18.8, respectively, were all observed with the Keck LGS AO system during engineering commissioning in 2005. All were observed using an LGS AO setup developed for observing faint science targets in which the target itself is used as the natural star reference. In LGS AO, there are quasi-static aberrations resulting from the parallactic elongation of the LGS as seen from the perspective of the fast wave-front sensor that strongly affect the image quality, and these aberrations change as the telescope pupil rotates. To keep the image quality as high as possible, these aberrations are measured and corrected on a bright nearby star, and the pupil angle is then kept fixed throughout the observations of the KBO. Fixing the telescope pupil, however, causes the image plane to rotate about the optical axis as the azimuth angle of the telescope changes throughout the observations.

Once the LGS AO system is set up, observing proceeds identically to standard IR observing procedures. All the KBOs were observed through a K' filter (1.948–2.299 μm) with the NIRC2 imager. The brightest three KBOs were imaged using

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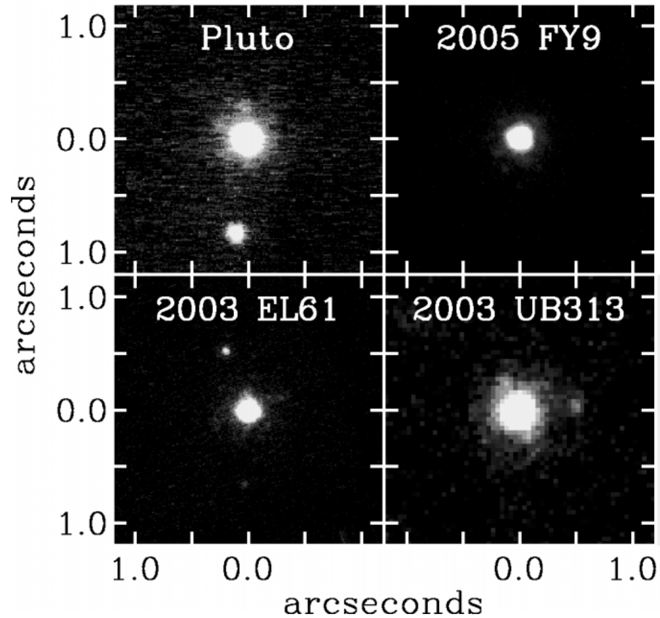

FIG. 1.—Images of the four brightest Kuiper Belt objects from the Keck Observatory Laser Guide Star Adaptive Optics system. All images are identically scaled logarithmically to the brightest point of the Kuiper Belt object and oriented with north up and astronomical east to the left. Satellites are seen clearly near Pluto (*directly below*), 2003 EL61 (*above left and directly below*), and 2003 UB313 (*directly right*). [*See the electronic edition of the Journal for a color version of this figure.*]

TABLE 1
SEPARATION OF 2003 EL61 AND ITS INNER SATELLITE

Date (UT)	Mean Time	R.A. Offset (mas)	Decl. Offset (mas)
2005 Mar 01	12:10	10 ± 30	520 ± 30
2005 Mar 04	11:36	<300	<300
2005 May 28	07:39	40 ± 40	−330 ± 40
2005 Jun 30	07:26	−40 ± 40	−650 ± 40

the 9.9 mas plate-scale camera, while 2003 UB313, which is fainter and consequently has worse correction, was imaged using the 39.7 mas plate-scale camera.

For Pluto, three 10 s exposures were taken at dither positions separated by 2″ on the detector, for a total integration time of 30 s. For 2005 FY9, six 60 s exposures were taken at each of the four dither positions, for a total integration time of 720 s. 2003 EL61 was observed five separate times with exposure times of 510, 600, 400, 780, and 360 s. For 2003 UB313, six 60 s exposures were obtained at each of the four dither positions, for a total integration time of 1440 s. The images were corrected for sky and instrumental background by subtracting the median of the images in each dither pattern. They were then flat-fielded using twilight sky flats, and known bad pixels were interpolated over. The individual images were then combined, correcting for rotation of the image with time, by shifting to a common center by cross-correlation.

Figure 1 shows Keck LGS AO images of the four brightest objects in the Kuiper Belt. The image of Pluto clearly shows its known bright satellite, Charon. We search for additional faint companions to Pluto by creating artificial point sources from scaled and shifted images of Charon. We find that we would have detected additional satellites around Pluto if they had a brightness of 0.4% relative to Pluto. The two probable satellites recently discovered by Weaver et al. (2005) are significantly fainter than these limits and would not have been detected in these observations.

No additional sources are seen in the field of 2005 FY9. Experimentation with embedding artificial sources shows that sources would have been detected with fractional brightnesses of approximately 3%, 2%, 1%, and 0.5% at distances beyond 0″.2, 0″.3, 0″.4, and 0″.5, respectively.

Two faint point sources are seen near 2003 EL61 on the image from the night of 2005 June 30, the night with the highest quality image correction. The brighter source is the well-characterized satellite discovered by Brown et al. (2005b). The second source appears in each individual frame and is stationary to a measurement error of 4 pixels with respect to the KBO over five separate observations spaced by a total of 5 minutes. A background star would have moved by 10 pixels during this time period. A faint source is also clearly seen in the full co-added observations of 2005 March 3. The source is too faint to be seen in individual exposures, but in two stacks of four 30 s exposures taken 6.8 minutes apart, the source is also stationary to a measurement error of 4 pixels. A background star would have moved 25 pixels between these two observations. Both of these sources are consistent with a relative brightness of 1.5% ± 0.5%, the brightness of the primary. In the 2005 March 4 image, a source consistent with this brightness is seen 0″.3 from the primary. The source remains stationary over a time period when a background star should have moved 23 pixels. At this small separation from the primary, point-spread function (PSF) artifacts are possible, although no artifacts of this brightness are seen in any of the other LGS AO images, so we tentatively consider the detection real. A source this faint would not have been detected in the lower quality 2005 January 26 image but would have been seen at a separation greater than 0″.4 in the 2005 March 1 image.

The three detections and the one significant nondetection (Table 1) appear consistent with the orbital plane of a satellite in a nearly edge-on orbit (Fig. 2). We use the χ^2-minimization method with Monte Carlo error estimates as described in Brown et al. (2005b) to first attempt a fit to a circular orbit assuming the already known mass of the primary. With four orbital parameters and only six data points, the fit is only marginally overconstrained. Circular orbits with periods of 34.7 ± 0.1 days or aliases at periods of 18.3 ± 0.1 and 19.2 ± 0.1 days can be fit to the data with χ^2-values of 1.4 and lower. Insufficient data exist to reliably attempt a fit to a noncircular orbit. The 34.7 day period orbits place the predicted position on 2005 March 1—the date of the only significant nondetection—within 0″.1 of the primary, where it would not have been detected. The shorter period orbits predict that the nondetection should have been almost 0″.6 from the primary and thus detectable. Based on the fit of the Keplerian orbit to the four separate observations, we thus conclude that we have indeed detected a second satellite around 2003 EL61. Figure 2 compares the plane-of-sky projections of the orbits of the two satellites of 2003 EL61, assuming the 34.7 day circular orbit. The two orbital planes are inclined by 39° ± 6° to each other. Additional high-resolution observations will be required to reliably determine the orbital parameters of this satellite. No additional fainter satellites could have been reliably detected.

One faint source is seen near 2003 UB313. The source is visible in most individual frames and is stationary over a length of time during which background stars (many of which are visible in the full 40″ field) smear by 7 pixels. Over the coarse

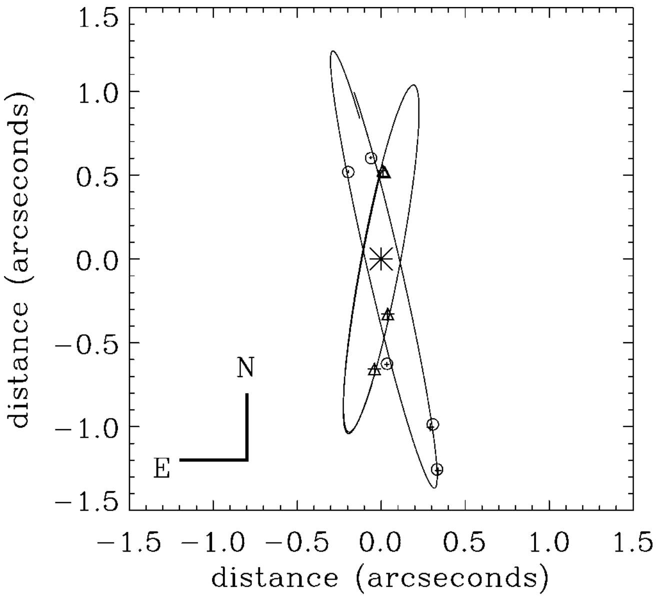

Fig. 2.—Projected orbits of the two satellites of 2003 EL61. Observations of both satellites and their measurement errors are shown. The predicted locations of the distant satellite (*circles*) and the close satellite (*triangles*) at the times of observation are also shown. For an assumed circular orbit of the inner satellite, the best fit gives an orbital period of 34.7 ± 0.1 days and a relative inclination between the two satellites of 39° ± 6°.

of the observations, the image plane rotated by 18°.3, which would have rotated any PSF artifacts at the position of the source by 4 pixels. No such motion is seen in the detected source. We thus conclude that the source is a satellite moving with 2003 UB313. With only a single observation of the satellite of 2003 UB313, we cannot yet measure or constrain the mass of 2003 UB313, but we can estimate likely orbital parameters to aid further study. If the satellite is on a circular (like Charon) or near-circular (like the larger 2003 EL61 satellite) orbit with a random orientation, then at any random point in time it is 50% likely to be at a separation within 14% of its semimajor axis. If the semimajor axis is 14% greater than the current separation, and if 2003 UB313 has the size estimated by assuming an albedo and density similar to Pluto's (Brown et al. 2005a), the satellite will have an orbital period of approximately 2 weeks. Observations over the coming season will allow us to make an accurate determination of the mass of this planetary-sized body.

3. DISCUSSION

Three out of four of the brightest known objects in the Kuiper Belt have satellites, and two of the four have multiple satellite systems (Table 2). The most extensive *Hubble Space Telescope* (*HST*) survey of the general KBO population to date found nine satellites out of 81 observations (Stephens & Noll 2006). The probability that these two populations have the same satellite fraction, f_s, can be calculated from simple binomial probability theory. Given nine satellites out of 81 observed objects, the probability distribution, $P[f_s]$, for f_s can be calculated as

$$P[f_s] = \frac{{}_9C_{81} f_s^9 (1-f_s)^{72}}{\int_0^1 {}_9C_{81} f'^9 (1-f')^{72} df'},$$

where ${}_9C_{81}$ is the number of unique ways to choose nine objects out of a sample of 81, calculated as 81!/(81 − 9)!9!. The probability, P_{3+}, that three or more out of four objects observed would then have a satellite is given by

$$P_{3+} = \int_0^1 P[f_s][{}_3C_4 f_s^3(1-f) +_4 C_4 f_s^4] df_s.$$

For the current sample, P_{3+}, the probability that the two populations have the same value of f_s, is equal to 0.9%. Thus, even with the very small sample involved, the result that the large KBOs and the smaller ones do not have the same probability of having a satellite is significant.

For many of the objects observed in the survey of Stephens & Noll (2006), faint satellites like those of 2003 EL61 and 2003 UB313 could not have been detected. Thus, the difference in fractional abundance between the two populations could simply be due to the greater relative depth of the LGS AO survey. A smaller but deeper *HST* program surveyed 19 satellites to a depth sufficient to have detected satellites with a fractional brightness of 1% within 0″.3 of the primary (C. A. Trujillo & M. E. Brown 2006, in preparation). This survey detected two satellites within these limits. Using the above binomial calculation, the probability that a sample of three or more out of for and of two out of 19 would be drawn from the same fraction is only 1.8%. Again, even with the small number of objects surveyed, the difference between the two populations is significant. We thus conclude that the overabundance of satellites around the brightest KBOs is intrinsic to this population rather than a function of survey limits.

TABLE 2
Parameters of Satellites of the Largest Kuiper Belt Objects

Parameter	Pluto	2005 FY9	2003 EL61		2003 UB313
Observing date (2005)	Sep 11.24	May 28.30	Jun 30.31		Sep 10.52
V magnitude	14.0	16.8	17.5		18.8
FWHM (arcsec)[a]	0.058	0.068	0.063		0.120
Strehl ratio[b]	0.37	0.20	0.18		0.10
Satellite fractional brightness (%)	19	<1	5.9 ± 0.5	1.5 ± 0.5	1.9 ± 0.5
Apparent semimajor axis (arcsec)	0.87	>0.4	1.3	1.0[c]	0.53[d]
True semimajor axis (km)	19640	…	49500	39300[c]	36000[d]
Orbital period (days)	6.4	…	49.1	34.1[c]	∼14[e]
Limits to additional satellites beyond 0″.4 (%)	<0.4	<1	<1.5		<1

[a] FWHM of the image of the primary, showing the near–diffraction-limited performance.
[b] Strehl is a measure of the peak intensity of the image compared to the theoretical expectation for a diffraction-limited image.
[c] Preliminary circular orbit fit.
[d] Observed separations only for 2003 UB313.
[e] Crude estimate (see text).

The satellites of 2003 EL61 and 2003 UB313 are much fainter, compared to their primaries, than any other known satellites except the possible new faint satellites of Pluto. None of these faint satellites appear likely to have formed from the process of dynamical-friction–aided capture thought to have occurred for many smaller Kuiper Belt objects (Goldreich et al. 2002) as this process requires that small bodies drain energy from the larger bodies to aid the capture. For bodies as faint as these satellites, dynamical friction would be essentially inoperable. Numerical simulations of a collisional origin for the Pluto-Charon system have been explored in detail (Canup 2005), and many of the potential system outcomes after an impact could lead to satellites with relative sizes similar to the 2003 UB313 and 2003 EL61 satellites. The simulated formation of these smaller satellites differs from the simulated creation of the Pluto-Charon system in that the large size and angular momentum of Charon are best produced by intact formation following the impact, while smaller-sized objects coalesce out of accretion disks similar to the one thought to have formed the Moon after an impact on the Earth. Formation in a disk has been shown to lead to a more rapidly spinning primary (Canup 2005), which could also explain the unusually rapid rotation of 2003 EL61 (Rabinowitz et al. 2006). Nothing is currently known about the rotation state of 2003 UB313, but the small secondary around 2003 UB313 might suggest a similarly rapid rotator. While simulations suggest that a giant impact with special geometry is required to explain the large mass fraction of Charon, smaller satellites appear to be able to form around Pluto-scale KBOs with a much wider range of impact geometries (Canup 2005). The formation of multiple objects in a disk might also help explain the multiple system around 2003 EL61, although further refinement of the orbital parameters will be required to more completely explore this possibility. While once Pluto appeared unique in the outer solar system in terms of size and satellite formation mechanism, it now appears to be one of a family of similar-sized objects with perhaps similar collisional histories and a range of satellite outcomes.

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 Universities 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. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We are grateful to Chuck Sorenson, James Lyke, Cynthia Wilburn, and Christine Melcher for their assistance with the observations, to Sniffen Joseph, David Collier, Nick Jordan, Teresa Kim-Pedro, and Michael Ruff for enduring long cold nights outside making sure the laser did not shoot down any airplanes, to Kris Barkume and Emily Schaller for discussions of Kuiper Belt object satellite formation and populations, and to an anonymous referee for some excellent suggestions.

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