Satellites of the largest Kuiper belt objects

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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), 2003 EL61, and 2003 UB313. The object 2005 FY9, the brightest Kuiper belt object after Pluto, does not have a satellite detectable within 0.4 arcseconds with a brightness of more than 0.5\% of the primary. The presence of satellites to 3 of the 4 brightest Kuiper belt objects is inconsistent with the fraction of satellites in the Kuiper belt at large at the 99.1\% confidence level, suggesting a different formation mechanism for these largest KBO satellites. The satellites of 2003 EL61 and 2003 UB313, with fractional brightnesses of 5\% and 2\% of their primaries, respectively, are significantly fainter relative to their primaries than other known Kuiper belt object satellites, again pointing to possible differences in their origin.

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

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1. Introduction

The discovery and orbital characterization of satellites to objects in the Kuiper belt has provided a unique window into the early history of the outer solar system. The early discovery of Charon (Christy & Harrington 1978) around Pluto and the seemingly 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 to 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 to the smaller Kuiper belt object 1998 WW31 with a satellite separation of almost three times the separation of Pluto and Charon and with a highly eccentric orbit was thus quite a surprise (Veillet et al. 2002). The large semi-major axis of the 1998 WW31 system leads to 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,b). The Pluto-Charon system, perhaps because of its size, has been the only binary system for which an entirely different formation mechanism has seemed necessary.

With the recent discovery of several KBOs approaching (and even exceeding) the size of Pluto, we have undertaken a survey of satellites in these systems in an attempt to determine if the Pluto-Charon system remains unique. Progress in surveys of newly discovered KBOs has been hampered in the past by the long lead time required to make observations from the Hubble Space Telescope. Recently, however, a new facility has become available for high spatial resolution imaging of KBOs from the ground. The W.M. Keck Observatory has just finished commissioning a Laser Guide Star Adaptive Optics (LGS AO) system for use with the Keck II telescope which is capable of obtaining infrared images with a similar resolution to that which the HST obtains for visible images (Wizinowich et al. 2005).

An LGS AO system works similarly to natural guide star (NGS) adaptive optics systems, which have now become standard on large telescopes throughout the world, in that the aberrations of starlight caused by the earth’s atmosphere are measured and removed by the system. An LGS system, however, instead of measuring the aberrations using the light from a bright natural star, measures aberrations from observations of 589 nm laser light resonantly scattered off of sodium atoms in a layer at approximately 90 km altitude in the earth’s mesosphere. While the use of the laser would ideally allow the LGS AO system to be used to image any location visible in the sky, the system has several practical limits that
can only be overcome by having at least one relatively faint natural star in moderately close proximity to the astronomical target. For current Keck LGS AO system performance, near diffraction-limited resolution at the K band (2.1 $\mu$m) requires a star with magnitude $V < 18$ within $\sim$60 arcseconds of the target (Wizinowich et al. 2005). Partial aberration correction can be obtained for a star up to a magnitude fainter (van Dam et al. 2005).

Moving KBOs occasionally come close enough to bright stars to be able to be observed with the LGS AO system, but four known objects in the Kuiper belt are bright enough that they themselves can be used as the natural guide star, and thus they can be observed without the time restriction imposed by the requirement of a background star. We present a Keck LGS AO survey for satellites around these four brightest known Kuiper belt objects.

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 of the KBOs were observed using an LGS AO setup developed for observing faint science targets where the target itself is to be used as the natural star reference. In LGS AO, there are quasi-static aberrations resulting from the parallactic elongation of the LGS from the perspective of the fast wavefront sensor that strongly affect the image quality, and these aberrations would rotate as the telescope pupil rotates. These aberrations are measured at a given pupil rotation angle using a bright nearby NGS. The pupil angle is then kept fixed on the fast wavefront sensor as the telescope is re-pointed to the KBO and throughout the observations, ensuring that the point spread function (PSF) remains as stable as possible (this step was skipped for Pluto which is bright enough itself to measure these aberrations). The image field, however, rotates about the optical axis as the azimuth angle of the telescope changes.

The tip-tilt mirror control loop, which provides fast telescope guiding to keep the science target precisely centered, is controlled using a quad cell of avalanche of photodiodes guiding on the KBO. The laser is then projected at the target and the resonantly scattered laser light is observed by a fast wavefront sensor which drives the 349-actuator deformable mirror to correct atmospheric aberrations. A final control loop controls the system focus. The focus of the system changes slowly due to changes in the structure of the mesospheric sodium layer. These focus changes are measured using a low-bandwidth wavefront sensor that looks at the KBO, and the measurement is used to drive the position of the fast wavefront sensor to be optically conjugate to the height of the sodium layer.

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 \( \mu m \)) with
the NIRC2 imager. The brightest three KBOs were imaged using the 9.9 milliarcsec plate
scale camera while 2003 UB313 was imaged using the 39.7 milliarcsec plate scale camera
since it is fainter and the correction is consequently worse.

For Pluto, three 10-second exposures were taken at dither positions separated by 2 arcsec
on the detector, for a total integration time of 30 seconds. For 2005 FY9 and 2003 EL61 six
60-second exposures were taken at each of four dither positions, for a total integration time
of 720 seconds. For 2003 UB313 six 60-second exposures were obtained at each of four dither
positions, for a total integration time of 1440 seconds. 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 satellite, Charon. Faint point sources are also
seen near 2003 EL61 and 2003 UB313, while none is seen around 2005 FY9. These faint point
sources are clearly not background stars or galaxies, as they move across the sky with the
same motion as the primaries. They also cannot be artifacts of the LGS AO system, as the
PSF of the LGS AO system rotates in the image plane during the course of the observations
and thus any PSF artifact would be smeared into an arc. We thus conclude that Pluto, 2003
EL61, and 2003 UB313 are circled by satellites. No satellite is seen in the vicinity of 2005
FY9. Experiments with embedding artificial point source into the 2005 FY9 field suggest
that a satellite with a fractional brightness of 0.5\% that of 2005 FY9 would have been seen
at a separation of 0.4 arcseconds or greater. Table 1 summarizes the detections or upper
limits of the satellites for these four brightest objects in the Kuiper belt.

After the initial Keck LGS AO discovery of the satellite to 2003 EL61, five observations
over the course of six months were used to determine that the mass of the 2003 EL61 system
is 4.2 \( \times 10^{21} \) kg or 32\% that of Pluto (Brown et al. 2005). 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 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
semi-major axis. An early search for a satellite to 2003 UB313 using NACO at the VLT
and a chance appulse with a bright natural guide star would have detected the satellite out
to a separation of approximately 0.4 arcseconds, but saw no satellite (Ivanov et al. 2005),
suggesting that the satellite does not spend all of its time at the current separation. 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. 2005), the satellite will have an orbital period of approximately two weeks. Observations over the coming season will allow 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. The most extensive Hubble Space Telescope survey of the general KBO population to date found 9 satellites out of 81 observations (Stephens & Noll 2005). The probability that these two populations have the same satellite fraction, $f_s$, can be calculated from simple binomial probability theory. Given 9 satellites out of 81 observed objects, the probability distribution, $P[f_s]$ for $f_s$ can be calculated as

$$P[f_s] = \int_0^1 \left[ \frac{9C_{81}}{9C_{81}} f_s^9 (1-f_s)^{72} \right] df_s,$$

where $9C_{81}$ is the number of unique ways to chose 9 objects out of a sample of 81, calculated as $81!/(81-9)!9!$. The probability, $P_{3+}$ that 3 or more out of 4 objects observed would then have a satellite is given by

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

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 satellites and the smaller ones do not have the same probability of having a satellite is significant.

While the survey of Stephens & Noll (2005) has not yet published detection limits, it is likely that for many of the objects observed in this survey, faint satellites like those of 2003 EL61 and 2003 UB313 would 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 arcseconds of the primary (Trujillo and Brown, in prep). This survey detected two satellites within these limits. Using the above binomial calculation, the probability that a sample of 3 or more out of 4 and 2 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. It thus appears that the overabundance of satellites to the brightest KBOs is intrinsic to this population rather than a function of survey limits.

The satellites of 2003 EL61 and 2003 UB313 are much fainter compared to their primaries than any other known satellites. Neither of these satellites appears 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 contain satellites with a 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 are formed in accretion disks similar to that 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. 2005). Nothing is currently known about the rotation state 2003 UB313, but the small secondary to 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 be formed around Pluto-scale KBOs with a much wider range of impact geometries (Canup 2005). 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.

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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. Satellites are seen clearly Pluto (directly below), 2003 EL61 (above and left; the faint source directly below is a trailed background star), and 2003 UB313 (directly right).
Table 1: Parameters of satellites of the largest Kuiper belt objects

|                              | Pluto  | 2005 FY9 | 2003 EL61 | 2003 UB313 |
|------------------------------|--------|----------|-----------|------------|
| Observing date (2005)        | 11 September | 28 May   | 30 June   | 10 September |
| V magnitude                  | 14.0   | 16.8     | 17.5      | 18.8       |
| FWHM (arcseconds)$^a$        | 0.058  | 0.068    | 0.063     | 0.120      |
| Strehl ratio$^b$             | 0.37   | 0.20     | 0.18      | 0.10       |
| Fractional brightness of satellite | 0.19       | < 0.005  | 0.05 0    | .02        |
| Apparent semi-major axis (arcseconds) | 0.87          | > 0.4    | 1.3       | 0.53$^c$  |
| True semi-major axis (km)    | 19640  | -        | 49500     | 36000$^c$  |
| Orbital period (days)        | 6.4    | -        | 49        | $\sim$14$^d$ |

$^a$Full width at half maximum 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.

$^c$Observed separations only for 2003 UB313.

$^d$Crude estimate. See text.