THE POSITIONS, COLORS, AND PHOTOMETRIC VARIABILITY OF PLUTO'S SMALL SATELLITES FROM HST OBSERVATIONS: 2005-2006.
S.A. Stern[1], M.J. Mutchler[2], H.A. Weaver[3], and A.J. Steffl[1]. [1]Southwest Research Institute, 1050 Walnut Street Boulder, CO 80302, astern@swri.edu, [2]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, [3]Space Department, 11100 Johns Hopkins Road, Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723.

Introduction: The discovery of two small satellites of Pluto and the initial orbit characterization for those satellites were described by Weaver et al. (2006). Additional confirmation was provided by new observations of the Pluto system using the HST ACS on 15 Feb 2006 and 2 Mar 2006 (Mutchler et al. 2006). The implications of these discoveries for the origin of Pluto's satellite system and the possibility of associated dust rings around Pluto were discussed by Stern et al. (2006). Steffl et al. (2006) used the combined HST dataset to set stringent upper limits on any additional satellites throughout the Pluto system, finding that any undiscovered satellites would have to be far fainter than either Nix or Hydra, except in the region between Pluto and Charon.

Observations and Astrometric Positions. All of our observations of Hydra (Pluto's outer small satellite) and Nix (Pluto's inner small satellite) were obtained with the HST using the Advanced Camera for Surveys (ACS). The observing circumstances on each of our four HST observing dates are described in Table 1. The telescope was programmed to track the apparent motion of Pluto for all of these observations. We used the ACS in WFC mode for the 2005 observations, and in HRC mode for the 2006 observations.

Table 1: Observation Summary

Date	Helio. (AU)	Geo. (AU)	Solar Phase (deg)
15.05 May 05	30.95	30.08	0.96
18.14 May 05	30.95	30.05	0.88
15.66 Feb 06	31.07	31.54	1.58
02.75 Mar 06	31.08	31.31	1.77

The F606W ("Broad V") ACS filter, which has a center wavelength of 591.8 nm and a width of 67.2 nm, was used on all four observing dates. To obtain color information, we additionally used the ACS F435W filter ("Johnson B"), which has a center wavelength of 429.7 nm and a width of 103.8 nm, on 2 Mar 2006. On all visits, unsaturated images of Pluto and Charon were obtained by using short exposure times of either 0.5 sec (the two May 2005 visits), 1 sec (Feb 2006 and Mar 2006 with the F606W filter), or 3 sec (Mar 2006 with the F435W filter); much longer exposure times (145 sec for the 2 Mar 2006 images using the F606W and 475 sec for all other long exposures) were used to obtain deep images of the new satellites, which are roughly 4000 times fainter than Pluto itself. Astrometric positions of Nix and Hydra, determined by centroiding with drizzle-combined (clean and distortion-corrected) ACS images, are given in Tables 2-4. To remove the known offset between Pluto's center-of-light and its center-of-body, all positions are referenced to Charon's center-of-light. For reference, we include the derived positions of Pluto's center-of-light, relative to Charon. Since Pluto was saturated in the long exposures, its position was derived by using its diffraction spikes and centroiding the short exposures.

Table 2: Nix Astrometric Positions

Date	Position Angle (deg)	Distance (")
15.05 May 05	335.9±0.7	2.84±0.04
18.14 May 05	355.6±0.7	1.36±0.04
15.66 Feb 06[1]	013.6±0.7	1.60±0.02
02.75 Mar 06[1]	223.9±0.7	1.89±0.02

Table 3: Hydra Astrometric Positions

15.05 May 05	289.7±0.7	1.96±0.04
18.14 May 05	286.7±0.7	1.96±0.04
15.66 Feb 06[1]	352.5±0.7	2.28±0.02
02.75 Mar 06[1]	149.5±0.7	2.52±0.02

Table 4: Pluto Astrometric Positions

15.05 May 05	357.3±1.0	0.84±0.05
18.14 May 05	175.9±1.0	0.85±0.05
15.66 Feb 06[1]	131.5±1.0	0.74±0.05
02.75 Mar 06[1]	252.9±1.0	0.55±0.50

Position angles and angular distances in Tables 2-4 are relative to Charon center-of-light. [1]These visits were split between two consecutive orbits.

Photometric Variability Measurements. V-band photometry of Nix and Hydra was obtained on three of the four HST visits (see Table 3). It was not possible to obtain accurate photometry for Nix and Hydra on one visit each in May 2005 because the satellites fell near diffraction spikes of Pluto. The V-band magnitudes shown in Table 5 were derived from instrumental magnitudes following Sirianni et al. (2005).

Table 5: Photometric V Magnitudes

Date	Hydra V Mag	Nix V Magnitude
15.05 May 05	N/A	23.38±0.17
18.14 May 05	22.93±0.12	N/A
15.66 Feb 06	23.26±0.10	23.70±0.10
02.75 Mar 06	23.30±0.10	23.57±0.10

Using the data in Tables 1 and 5, we normalized the various V magnitude measurements of Nix and Hydra, adjusting for the changing heliocentric and geocentric distances, and for the changing solar phase angle. For the phase angle correction, we assumed that Nix and Hydra follow Charon's phase law (Tholen & Buie 1997). After making these corrections, we find that the relative brightnesses of Hydra on its three observing dates are 1.00:0.87:0.84, and the values for Nix are 1.00:0.87:0.98. The observed relative brightness changes are not large; they indicate that the relative changes in effective radius presented to us on the various observing dates fluctuated by <14%. Of course, our temporal sampling is sparse and presumably does not provide a good characterization of the lightcurve of either Hydra or Nix. Nonetheless, if Nix and Hydra have Charon-like albedos of 0.35, their nominal diameters are just 61 and 46 km, respectively (Weaver et al. 2006). Such small bodies often display diameter variations of order 2:1 as they rotate, which would produce relative photometric variations of up to a factor of four, depending on the pole orientation.

Why might Nix and Hydra display smaller fluctuations? One explanation might be that we serendipitously observed both satellites at times when the same faces were presented to us; this is unlikely but certainly possible. Another possibility is that Nix and Hydra might have albedo variations that serendipitously compensate for cross-sectional changes, another unlikely possibility. A third possibility is that Nix and Hydra, in fact, have substantially lower albedos than Charon. For example, if both have geometric V albedos of 0.04, then their diameters are 167 and 137 km, respectively (Weaver et al. 2006). Bodies having diameters >140 km are typically rounder than bodies that are much smaller. Thus, the lack of brightness variations in our data could be hinting that Nix and Hydra may be larger and rounder than they would be if they had Charon-like albedos.

Color Measurements. On 2006 March 2.75, we obtained images of the Pluto system using both the HRC F435W and F606W filters. This allowed us to obtain simultaneous B and V photometry for Nix and Hydra, which in turn allows us the opportunity to obtain surface colors. Using the background-subtracted B and V count rates of each object, and adopting Charon's B-V=+0.710 (Buie et al. 1997) as a calibration reference, we derive B-V colors of +0.653±0.026 and +0.654±0.065 for Nix and Hydra, respectively. From these colors, we conclude that all three of Pluto's satellites display similar, essentially solar colors; this in turn implies that they all have grey intrinsic surface reflectances in the visible. Buie et al. (2006) also found a neutral B-V color for Hydra in lower-SNR measurements made by co-adding archival Pluto-system images in 2002 and 2003. However, they found a much redder B-V=+0.91±0.15 for Nix from similar SNR data. Our results indicate that the red color suggested for Nix by Buie et al. is an artifact; both Nix and Hydra have a B-V color similar to Charon.

Acknowledgements. Support was provided by NASA Grants GO-10427 and GO-10774 from Space Telescope, operated by the Association of Universities for Research in Astronomy, and by New Horizons.

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